Research

Filipe Nascimento, Luísa Quintino

Developments in Friction Stir based technologies

Abstract: Solid state techniques have been widespread and have the potential to be introduced in several industries solving problems that are not possible to resolve through the more common technologies. Friction Stir Welding is a welding technique based on friction mechanisms that has been studied since its discovery on 1991. This technique can weld aluminium and copper alloys and is of particular interest for the energy sector. Friction stir technology is widely used for welding aluminium through its potential reaches other areas. The present paper covers examples of applications of friction stir welding, surfacing and channelling, with potential for industrial implementation. The present paper depicts one example application in the replacement of copper by aluminium in electric power transformers which is of particular interest due to the savings that can be reached. A feasibility study has been carried out in which it is demonstrated that this process can effectively weld thin aluminium and copper plates producing very good results in the material mechanical and electrical properties. It was also confirmed that this process can effectively weld aluminium to copper however some restrictions must be made to guarantee a sound weld. Surfacing techniques are of particular interest because they can improve the mechanical properties of a certain material making it more robust to the environmental conditions. Developments in friction stir processing and friction surfacing are shown and result in improvement of the mechanical properties compared to the base material. It was concluded that both these processes can be used as surfacing techniques and usually the processed area presents better mechanical, wear and corrosion properties than the substrate. Friction Stir Channelling is a novel technique that can have a widespread application in the mould industry as it is a suitable technique for the production of internal conformal channels. An example focusing the production of two prototypes for the mould industry with the objective of rapidly homogenizing the surrounding temperature is presented in this paper.

Keywords: Aluminium alloys, Friction Stir Welding, Surface Modification, Friction Stir Channelling

Filipe Nascimento, Luísa Quintino - Instituto Superior Técnico, Universidade de Lisboa, IDMEC, Instituto de Engenharia Mecânica – Pólo IST,Lisbon, Portugal

Introduction

Friction stir technology is widely used for welding aluminium through its potential reaches other areas. The present paper covers examples of applications of friction stir welding, surfacing and channelling, with potential for industrial implementations.

Friction stir based technologies have been in the forefront of scientific development and different works have been developed to improve the process and to apply it to new materials and joints. Several works focus on the application of this process in novel ways and study the effects of this process in new materials.

The improvement of properties is related to grain size refinement and homogenization due to the large processing strains in the nugget [3]. Cavaliere et al. [4] studied the evolution of the microstructure and mechanical properties of an AA6082 alloy with the different process parameters. It was observed that the grain size decreased with an increasing transverse speed. These results are aligned with the FSW principles because with the increasing transverse speed, the weld will be in a colder state and therefore the grain size will be smaller.

Several authors [5]–[7] have studied the effects of FSW parameters in different aluminium alloys to understand the best parameters to have the best joining efficiency of a weld. It was observed that the joining of different aluminium alloys is possible and that the properties are usually between the properties of the base materials [8], [9]. Most studies have been focused on parameters' influence in the properties of the welded samples. This creates a need for a structured approach that can help in understanding the interaction between the welded samples properties and process parameters. Taguchi method is a method to do that and it has been applied to other friction stir processed aluminium alloys [10], [11] however no definite relationship has been established in these studied alloys.

Recent developments have focused on the study of the mechanical properties of the friction stir welded materials. Casalino et al. [12] have studied the effect of shoulder geometry and tool coating in the mechanical properties of an aluminium alloy. It was observed that flat shoulder showed some sensitiveness to the material properties and that the thermomechanically affected zone (TMAZ) grain size was dependent of the shoulder diameter. Another work focused their studies on the microstructural evolution of the friction stir welded samples [13]. In the dissimilar alloys of different aluminium alloys it has been concluded [14] that the joint has a high level of residual stresses and that the residual stress increases with the rotational speeds which affects negatively affects the properties of the dissimilar joints. One author [15] has confirmed that the final yield strength is dependent on the remaining solid solution which may compensate the loss of strengthening effect of larger precipitates in a lower volume fraction. It has been confirmed that the mechanical properties can improve with an offset of the pin this has also been confirmed [16] for fatigue properties of a dissimilar weld between AA2024 and AA7075 alloys. It was observed that the fatigue properties improved when the pin was moved up to 1mm to the AA2024 side. A study in the properties of ageing effects [17] has shown that the properties do not vary much between aged and non-aged samples. Other studies have shown [9], [18] that the fracture of the materials can be related to several mechanisms like the increase in the residual stresses in the nugget area or existent irregularities. In the weld of different alloys of magnesium [19] it has been observed that the position of the different alloys and the advancing speed are very important in definition of their mechanical properties.

Surface engineering is one of the most relevant current fields of research. The events that occur on the surface, such as wear, corrosion or stress concentration create regions prone to crack nucleation, which under static or dynamic loading will eventually lead to most components and structures failures. This results in important losses in repairs or unscheduled maintenance operations. Recently, solid state coating techniques have been exploited, since they produce similar outcomes while avoiding the common defects inherent to fusion based processes [20]. Among these, Friction Surfacing (FS) is best known for enabling dissimilar material combinations. Substrate distortion and degradation of material properties are limited, while the coating material is provided by the consumable rod with no external heat source [22]. However, the coating cross section presents unbonded edges on both the advancing (AS) and retreating sides (RS), which are closely related to process parameters. The process is also characterized by the constant generation of a revolving flash at the rod tip, responsible for the mushroom-shaped upset on the consumable rod.

With special focus in the manufacturing of long-life cutting tools it has been used for wear resistant hard facing, anti-corrosion coatings and in the rehabilitation of worn or damaged parts such as, turbine blades, railways, agricultural machinery [23]. A wide range of materials combinations has been deposited by friction surfacing, mainly tool steels, stainless steels, mild steel, copper and nickel-based alloys [24]–[26].

The Friction Stir Channelling (FSC) process was initially based on converting an internal defect in FSW joints: the "wormhole" defect, into a manufacturing technique where all the material extracted from the workpiece laid on the processed zone below the shoulder [27], within a clearance between shoulder and workpiece. The first work published [27] has shown that by selecting the optimal processing parameters and reversing the material flow pattern of FSW it is possible to produce continuous channels. The respective patent was published in 2005 and since then, significant developments have been achieved.

The geometry of the channel can be controlled by varying the following parameters: the clearance between workpiece and tool shoulder, the tool rotation speed and travel speed and the tool design [27]. An evolution of the FSC tool was developed [28] which enables the material removed by the process to be cleared out as the channel is being produced leaving the workpiece with the same level and surface finish as it had before the channel. The material that comes from the base of the probe is pushed outwards by the scrolls on the shoulder because there is no clearance between shoulder and workpiece. This major difference also has an impact on the characteristics of the channel: size, shape, roughness and mechanical properties, compared to the FS channels produced by other researchers [27]. The developments made [28] allowed FSC to produce channels of greater dimension, rougher surfaces and bigger "wet surfaces". Consequently, all of the mentioned features enable more industrial applications for FSC.

Recent developments

Friction Stir Welding

One of the projects that were carried out intended to assist in the industrial implementation of Friction Stir Welding (FSW) process in components of electric power transformers. A methodology based on the Taguchi method was used to estimate the optimal parameters of butt welds in thin sheets of a 1.6mm thick AA1070 aluminium alloy and a 1.1mm thick C11000 copper alloy. For this study, three levels of the parameters were varied: Axial Force (Fz), Travel Speed (Vx), and Probe Length (Lpin). The optimum parameters were obtained through an analysis of variance (ANOVA) on three factors of overall efficiency, being those GET, GEB and HARD. They were reached based on the results of tensile, bending and hardness, respectively and also tested solutions for welding together both materials.

Two Taguchi studies were made, one for aluminium and the other for copper butt-welding. In both studies the evaluation and control parameters, as well as the orthogonal array applied, were the same. The nominal values of those parameters were obviously adjusted to each condition.

Three factors were used to evaluate the overall quality of the different trials, based in the mechanical response of the welds. The first of those global analysis factors, Global Efficiency on Tensile (GET), eq. (1), was developed by Vilaça, P. [29].

$$GETS = 0{,}1 \times \frac{E}{E_{BM}} + 0{,}3 \times \frac{\bar{\sigma}_{0,2}}{\bar{\sigma}_{0,2_{BM}}} + 0{,}2 \times \times \frac{\bar{\sigma}_{max}}{\bar{\sigma}_{max_{BM}}} + 0{,}25 \times \frac{\bar{\varepsilon}}{\bar{\varepsilon}_{BM}} + 0{,}15 \times \frac{U_T}{U_{T_{BM}}} \quad (1)$$

In analogy to GET, Vidal et al. [10] developed Global Efficiency on Bending (GEB), shown in. eq. (2), and the Hardness Coefficient (HARD) that appears in eq. (3).

$$GEB = 0{,}5 \times \frac{F_i}{F_{BM}} + 0{,}25 \times \frac{d_i}{d_{BM}} + 0{,}25 \times \frac{U_{B_i}}{U_{B_{BM}}} \quad (2)$$

$$HARD = \frac{Minimum\ hardness}{BM\ hardness} \quad (3)$$

These three evaluation factors represent in percentage the performance of each trial, according to the base material values weighted by the importance between the various properties obtained for each test. As the aim is to find the best set of parameters for three different control parameters (F, V and L) over a window of three defined values (Level 1, 2 and 3) it is used the Taguchi L9 orthogonal array (OA), with just three columns, as depicted in Table 1.

Table 1. Taguchi L9 Orthogonal Array with 3 columns

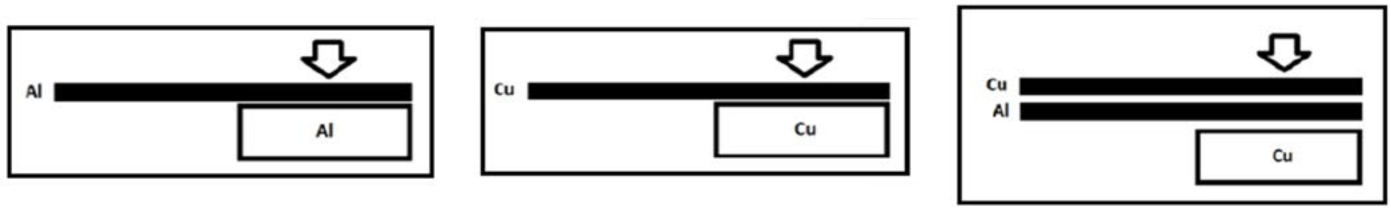
Trial	Force (Fz)	Speed (Vx)	Length (Lpin)
1	F1	V1	L1
2	F1	V2	L2
3	F1	V3	L3
4	F2	V1	L2
5	F2	V2	L3
6	F2	V3	L1
7	F3	V1	L3
8	F3	V2	L1
9	F3	V3	L2

In the aluminium alloys, tensile results revealed that the optimum set of parameters for Global Efficiency on Tensile, were F2, V3 and L2, with the probe length being the most influencing parameter and Axial Force the most negligent. The Three Point Bending results, showed a large dependence on force and little relation to travel speed. The optimum parameters were F1, V3 and L3. The Hardness coefficient was mainly dependent on travel speed variation and indifferent to probe length. The best results were obtained with F3, V1 and L3 parameters levels.

In the copper the same analysis was performed and revealed that the optimum set of parameters for Global Efficiency on Tensile, were F1, V1 and L2. The travel speed was the most important parameter, with 45.68%. The bending and hardness results show that the influence of the chosen parameters is negligible for the obtained performance in these trials. Since the error is bigger than the influence of the parameters it means that the results for these properties should not be taken into consideration.

The confirmation samples showed that the obtained combinations were able to provide the strength and properties that make the friction stir welding process acceptable for this welding of components of electrical transformers.

The joining between those sheets and end-bars of the same materials and welds made with visually satisfactory characteristics was also a subject of investigation. Foil-Bar welding was also required from the client. Those welds are essential and irreplaceable in the present foil winding manufacture. For each foil winding, two mandatory foil-bar welds are performed, to the entrance bar and end-bar. From the client engineering point of view these components are not subjected to high mechanical stresses. So there was no necessity to perform optimization or characterization tests, as the objective of this preliminary



Parameter	Min	Max
Fz (Kg)	200	300
Vx (mm/min)	150	300
Ω (rpm)	1000	1200

Parameter	Min	Max
Fz (Kg)	700	1000
Vx (mm/min)	150	250
Ω (rpm)	800	1200

Parameter	Min	Max
Fz (Kg)	450	600
Vx (mm/min)	180	210
Ω (rpm)	800	1000

Fig. 1. Different tested material combinations and tested parameters

study was only to achieve a range of parameters that could perform acceptable welds. The geometry used was overlapped. In theory this weld could also be done in a corner joint in order to save material, using a side tilt angle.

The set of welds were made to understand the feasibility of this welding process for the following welds:
- Aluminium foil-bar,
- Copper foil-bar,
- Aluminium foil – copper bar.

This analysis allowed concluding that the process can easily weld the aluminium foil-bar and copper foil-bar. However, some disturbances were observed in the analysis of the aluminium foil – copper bar combination due to the forces in the flow of material the aluminium would blow-off from the processed area. The developed solution involves overlapping a small foil of copper over the aluminium and this foil would be able to constrain the aluminium and avoid the blow-off of the aluminium from the processed area (Figure 2).

Fig. 2. Image of the overlap welded aluminium copper.

Surface modification

There are several ways to modify the properties of the surface of a material in order to improve the properties of the materials and make the material more resilient to the work conditions. Two processes based on friction mechanisms have employed towards this goal:
- Friction Stir Processing (FSP) using a non-consumable tool,
- Friction Surfacing (FS) using a consumable tool.

FSP is a technique that is based on the same concepts as the FSW in which a rotating non-consumable tool penetrates in a material and through the strains promoted by the process it is able to promote the dynamic recrystallization of the processed area. It has been confirmed that the properties in this area [2] are interesting because the small, homogeneous grains promote good mechanical properties. These properties are sometimes better than the mechanical properties of the base material.

Developed works using the non-consumable tool have focused on the multi-pass techniques to improve the superficial properties of the used material. One of the concerns that has been made is to guarantee that the properties of the preceding pass(es) are not changed by the posterior pass(es) while improving the mechanical properties of the base material. Taking into account this goal, an AA5083-H111 aluminium alloy was processed at a rotation speed of 1000 rpm and a tool travel speed of 25 mm/s using the multipass technique while moving half

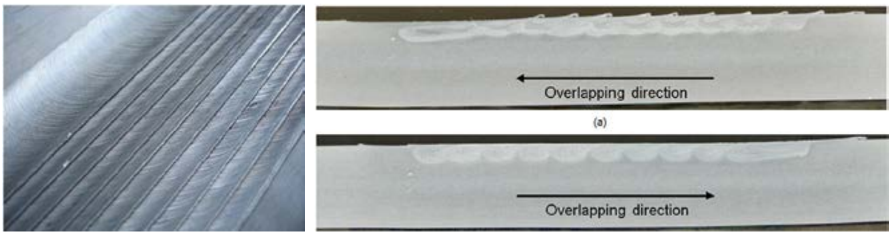


Figure 3 – Aluminium AA5083-H111 processed through FSP [31]

the pin diameter between passes (Figure 3). It was observed that this method is able to process large surfaces. Two situations were observed in this analysis regarding the process characteristics, the effect of the overlap on the advancing side of the process and the effect of making the passes on the retreating side.

For this goal, different mechanical characterization tests to assess the improvement of the mechanical properties were used. Hardness tests confirmed that the performed passes do not change the mechanical properties of the preceding passes since there is a hardness in the processed area. It was also observed the homogeneity of the hardness with the consecutive passes in this alloy.

Table 2. Bending results of the processed samples [31]

	BM	Overlap AS		Overlap RS	
		Tensile	Compression	Tensile	Compression
Load (kN)	14.16	15.67	16.11	16.04	16.76

The bending tests confirm the improvement of properties that was observed in the hardness testing. It has been observed that executing the passes in the retreating side (RS) seem to bring better bending properties. This result is probably related to the fact that doing the overlap this way results in a much smoother surface than the other tested options and therefore will result in a lower number of possible defects. To summarize, the applicability of FSP as a surface treatment technique has been proven and the practical cases have shown improvements of the mechanical properties of the processed areas.

Friction Surfacing (FS) is a solid state coating process where a rotating consumable rod will be deposited on the surface of an alloy. The heat generated by frictional dissipation promotes the viscoplastic deformation at the tip of the rod. This technique has several advantages, although one of its most promising applications is in repairing used materials. The influence of the different parameters is as follows:

- The forging force, improves the bonding extension, resulting in wider and thinner deposits. Excessive force will result in a non-uniform deposition due to the expelling of material from the back;
- Rotation speed influences the bonding quality and the coating width and roughness. Lower rotation speeds promote the bonding quality while higher rotation speed promotes regular and flat deposits;
- Travel speed strongly influences the coating thickness and width since it defines the rate at which the material is deposited;
- Tilt angle – increasing the tilt angle has proven to improve the bonding at coating edges thereby increasing the bonded interface;
- Consumable diameter – the coating thermal exposure is a function of the rod diameter.

The joining mechanism of this process is the superficial diffusion resulting in a hot forged metallic structure. Several studies have been made to confirm the efficiency of the deposition, an example is the deposition of AA6082 alloy over a 2024 aluminium alloy to improve the bending and wear behaviour [32]. It was confirmed that even though the coating had good bending properties, the wear behaviour was better at AA2024 substrate plates due to it higher hardness. A good bonding between the AA6082 aluminium alloy with the AA2024 aluminium alloy which confirms the applicability of this process to dissimilar material was observed. This coating, if applied in an area condition can

Fig. 4. Case study on corrosion properties: Stainless steel on mild steel (left) and AA6082 on AA2024 (right)

help improve the corrosion resistance of a given material. To accomplish this, the added material should have better corrosion properties than the substrate, like the case studied above.

To study the effectiveness of corrosion protection, two solutions were tested. The first one was the coating of a mild steel with a stainless steel material that was machined at a later stage, and the second was the coating of a AA2024 aluminium alloy with a AA6082 aluminium alloy. It was clearly visible that the added alloys which were more resistant to corrosion than the substrates were not influenced by the corrosive environment. This result has also shown that there is a need for the corrosion resistant material to cover the full area of the substrate because the unprotected substrate will corrode resulting in a rougher surface.

This technique is very interesting however it is needed to confirm the degree of applicability of this technique in a wide range of possible industry cases. For this, it was studied the application of this technique in surface coverage, conformal paths and build-up solutions. In the surface coverage the material was tested to observe the effect of doing consecutive passes to observe if there was any distortion due to process instability. This was also applied in different surface conditions to observe the full capability of this process.

It was observed that the application of the multipass technique is effective (Figure 5 left) as there is no visible instability and there is a continuity of the coating in the different tested conditions. The versatility of this process is also observed since it can be effectively applied to curved surfaces with regular deposits (Figure 5 centre). It is also possible to observe that this process can be applied to irregular surfaces; however, there seems to exist some instability in the deposited material in this case (Figure 5 right). This last case shows that this process can be used as a build-up solution by depositing several layers. (Figure 6 left).

The implementation using conformal paths for the coating seems to be promising showing the deposited material has a regular shape. Figure 6 shows a curve with an optimized shape of the deposit with good bonding properties. It has been confirmed that this process can effectively coat different material and that this process can be widely used in different substrate conditions. Therefore, the wider application of this process has been considered for a wide variety of industries.

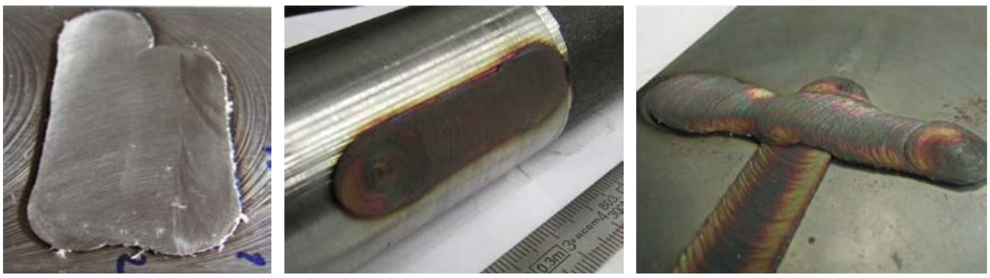


Fig. 5. Different tested surface conditions

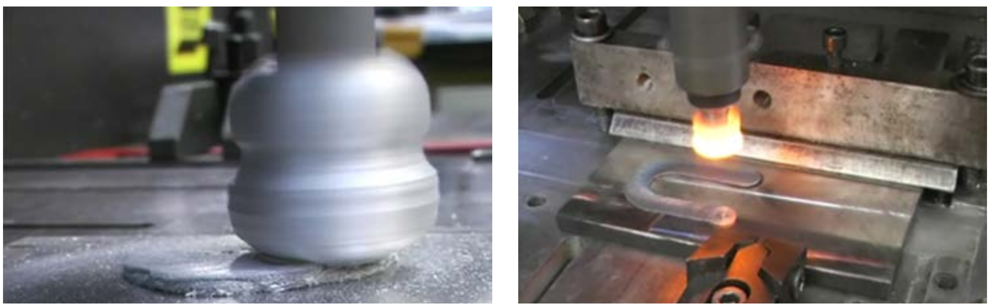


Fig. 6. Possibilities of the application of Friction Surfacing: build up (left) and conformal coatings (right)

Friction Stir Channelling (FSC)

FSC is a technique that is able to produce conformal channels inside monolithic materials and can be used in several industries, and the mould industry is an example where it can be more efficiently applied to produce cooling chanels. Usually drilling, electric discharge machining (EDM) and milling are the techniques used to produce channels in mould industry. FSC presents several advantages when compared to these technologies. When compared to drilling it can produce conformal channels which can also vary the channel depth compared to the surface providing a more homogenised cooling of the studied part. The production cost is an advantage over the EDM, which also includes the cost of the dielectric fluid that is very costly. Drilling can make conformal channels providing a homogenised cooling in the produced parts; however, this technique is limited to the production of open channels, and therefore, it is needed at least two steps to create a cooling system using this technique. FSC can achieve the same results in one step, and the produced part will need little to no finishing after concluding the operation.

Two prototypes were developed to verify the potential and applicability of this process in the mould industry. The first prototype intends to evaluate the capabilities of FSC to manufacture conformal cooling channels that depends on fast production cycle times. The second FSC application relies on slower heating/cooling processes with insignificant variations in temperature, in comparison with time variations. When long duration heating/cooling cycles are required, the channels have bigger lengths and more complex paths. The ultimate aim is to obtain elevated workpiece surface quality due to uniform heating/cooling processes provided by well distributed FS channels.

The first prototype intends to present the feasibility of the FSC process to produce conformal cooling channels in mould manufacturing while showing the flexibility of the FSC process in the production of the different channels path and at different depths. A prototype was modelled and simulated using Solidworks Floxpress® using water as the cooling liquid. The simulation steps were performed to optimize the cooling of the part by designing the different channels and defining the best lengths and curvatures of the cooling channels (Fig. 7).

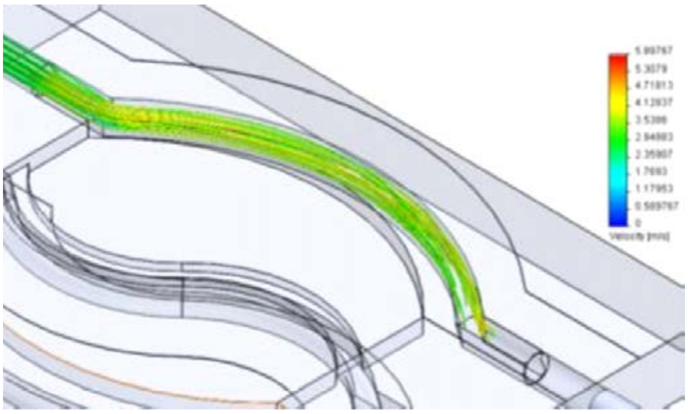


Figure 7 - Cooling fluid flow simulation in one FS channel of injection mould

The channels were produced using an FSC tool with a pin diameter and length of 8mm and the conic pin with a left-handed square thread. The scrolled shoulder had a diameter of 20mm (Figure 8). The process was conducted by applying a force of 420kg, using a tool travel speed of 100mm/min and tool rotation speed of 400rpm.

Fig. 8. Tool used to produce the injection mould prototype

One of the findings of this work is related with the cooling purpose. It was observed that to properly cool the mould the channel length must be limited. If not, the cooling purpose is lost, causing the liquid to be heated while travelling on the channels.

The manufacturing feasibility of this process was confirmed, and it was observed that it possible to produce conformal channels in the monolithic parts to homogenize the cooling of the different parts. One of these parts (Fig. 9) has three channels at different planes that can improve the cooling rate of the different components. Figure 9 also shows that the shape of these channels is maintained the same in the different curvatures that are needed to make to produce this part. This is also an important factor because since there are very small changes in the channel, the pressure of the cooling liquid will be constant.

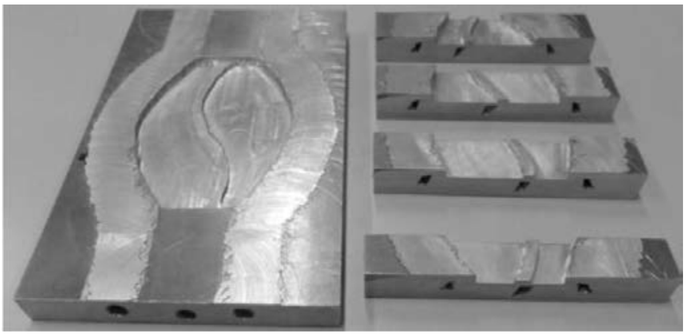


Fig. 9. Prototype of the injection mould prototype

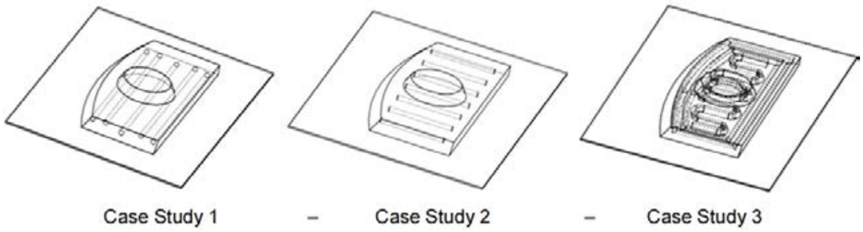


Fig. 10. Different scenarios studied

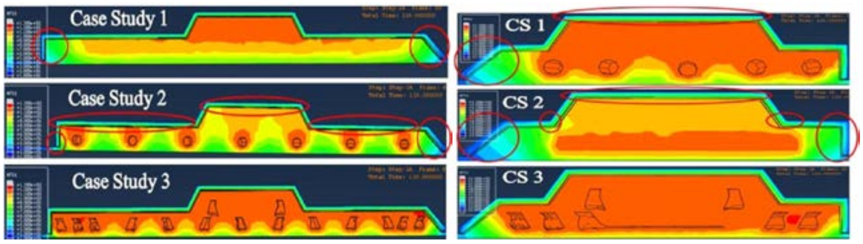


Fig. 11. Simulation results of different scenarios in two planes

The second prototype intends to show the feasibility of using FS channels in a curing process mould. In this case the goal is homogenize the heating surface to have a uniform temperature distribution in a complex mould configuration. This way there will be a reduced number of problems in production of these parts.

Fig. 12. Tool used to produce the curing mould prototype

In the same way as the first prototype, a thermal analysis was performed in the parts. In this case, different scenarios were taken into account to compare to the temperature distribution of drilling process option. Two scenarios were studied for the drilling (Case study 1 and 2) in which the channels were produced in two different directions in straight path. The FSC scenarios present the use of serpentine paths that can optimize the thermal distribution of the part (Figure 10).

The simulation made took into account the usual shape of the channel produced by the FSC process. The simulation results show that the use of the FSC configuration is able to homogenize the temperature in the mould and eliminate differences that might occur due to poor temperature distribution as observed in the other two scenarios. This presents a great advantage of the FSC over the other manufacturing techniques, in this case the limitation regarding the length of the channels presented becomes an advantage that can homogenize the temperature in the mould.

The channels of the curing process prototype were produced using an FSC tool with a pin diameter and length of 8mm and a cylindrical pin with a left-handed square thread. The scrolled shoulder had a diameter of 19mm (Figure 12). The process was conducted by applying a force of 500kg using a tool travel speed of 100mm/min and tool rotation speed of 600rpm.

This choice of parameters allows the extraction of a bigger rate of material improving the channel volume and which ultimately can improve the temperature distribution of the mould. The serpentine profile is very useful for this goal and it has been confirmed that the longer routes effectively increase the heat in the channels and improve the curing process in these parts.

Fig. 13. Prototype with serpentine profile

Conclusions

Friction stir technology has shown potential for a variety of industrial applications focusing in welding surfacing and channelling in specific cases identified by manufacturing companies.

The use of FSW to replace the TIG process in copper welding and in the introduction of aluminium alloys in the fabrication of components for transformers has shown promising results since good welding in similar and dissimilar joints were obtained with adequate mechanical and conduction characteristics.

Surface techniques have brought very good results in the improvements of the surface properties of a range of selected materials. It was observed that the mechanical properties of a material processed by both processes usually had better properties than the substrate. It also confirmed the flexibility of the friction surfacing process that can have stable results with different substrate and working conditions.

Friction stir channelling is an innovative technique that can be widely applied to mould industry. It was observed that for the cooling of the injection moulds some restraints should be made regarding the channel length because the increase in temperature would eventually lead to increase fluid in the channel and reducing the cooling effect. It was also observed that these same channels are ideal for curing processes that need to increase the temperature and the use of serpentine channels will aid in having a more homogeneous temperature distribution.

Acknowledgements

We would like to acknowledge the Foundation for Science and Technology (FCT), Lisbon, through the 3º Quadro Comunitário de Apoio, and the POCTI and FEDER programmes.

References

1. T. M. Wayne, E. D. Nicholas, J. C. Needham, M. G. Murch, P. Templesmith, and C. J. Dawes, “Improvements relating to friction welding,” WO/1993/010935, International Patent Number PCT/GB92/02203,1992.
2. R. S. Mishra and Z. Y. Ma, “Friction stir welding and processing,” Mater. Sci. Eng. R Reports, vol. 50, no. 1–2, pp. 1–78, Aug. 2005.
3. F. Nascimento, T. Santos, P. Vilaça, R.M. Miranda, and L. Quintino, “Microstructural modification and ductility enhancement of surfaces modified by FSP in aluminium alloys,” Mater. Sci. Eng. A, vol. 506, no. 1–2, pp. 16–22, Apr. 2009.
4. P. Cavaliere, A. Squillace, and F. Panella, “Effect of welding parameters on mechanical and microstructural properties of AA6082 joints produced by friction stir welding,” J. Mater. Process. Technol., vol. 200, no. 1–3, pp. 364–372, May 2008.
5. D. M. Rodrigues, A. Loureiro, C. Leitao, R. M. Leal, B. M. Chaparro, and P. Vilaça, “Influence of friction stir welding parameters on the microstructural and mechanical properties of AA 6016-T4 thin welds,” Mater. Des., vol. 30, no. 6, pp. 1913–1921, Jun. 2009.

6. P. Cavaliere, A. De Santis, F. Panella, and A. Squillace, "Effect of welding parameters on mechanical and microstructural properties of dissimilar AA6082–AA2024 joints produced by friction stir welding," Mater. Des., vol. 30, no. 3, pp. 609–616, Mar. 2009.
7. K. Elangovan and V. Balasubramanian, "Influences of tool pin profile and welding speed on the formation of friction stir processing zone in AA2219 aluminium alloy," J. Mater. Process. Technol., vol. 200, no. 1–3, pp. 163–175, May 2008.
8. P. M. G. P. Moreira, T. Santos, S. M. O. Tavares, V. Richter-Trummer, P. Vilaça, and P. M. S. T. de Castro, "Mechanical and metallurgical characterization of friction stir welding joints of AA6061-T6 with AA6082-T6," Mater. Des., vol. 30, no. 1, pp. 180–187, Jan. 2009.
9. S. T. Amancio-Filho, S. Sheikhi, J. F. dos Santos, and C. Bolfarini, "Preliminary study on the microstructure and mechanical properties of dissimilar friction stir welds in aircraft aluminium alloys 2024-T351 and 6056-T4," J. Mater. Process. Technol., vol. 206, no. 1–3, pp. 132–142, Sep. 2008.
10. C. Vidal, V. Infante, and P. Vilaça, "Assessment of improvement techniques effect on fatigue behaviour of friction stir welded aerospace aluminium alloys," Procedia Eng., vol. 2, no. 1, pp. 1605–1616, Apr. 2010.
11. A. K. Lakshminarayanan and V. Balasubramanian, "Process parameters optimization for friction stir welding of RDE-40 aluminium alloy using Taguchi technique," Trans. nonferrous Met. Soc. China, vol. 18, pp. 548–554, 2008.
12. G. Casalino, S. Campanelli, and M. Mortello, "Influence of Shoulder Geometry and Coating of the Tool on the Friction Stir Welding of Aluminium Alloy Plates," Procedia Eng., vol. 69, pp. 1541–1548, 2014.
13. I. Kalemba, C. Hamilton, and S. Dymek, "Natural aging in friction stir welded 7136-T76 aluminum alloy," Mater. Des., vol. 60, pp. 295–301, Aug. 2014.
14. A. Steuwer, M. J. Peel, and P. J. Withers, "Dissimilar friction stir welds in AA5083–AA6082: The effect of process parameters on residual stress," Mater. Sci. Eng. A, vol. 441, no. 1–2, pp. 187–196, Dec. 2006.
15. C. Jonckheere, B. de Meester, A. Denquin, and A. Simar, "Torque, temperature and hardening precipitation evolution in dissimilar friction stir welds between 6061-T6 and 2014-T6 aluminum alloys," J. Mater. Process. Technol., vol. 213, no. 6, pp. 826–837, Jun. 2013.
16. P. Cavaliere and F. Panella, "Effect of tool position on the fatigue properties of dissimilar 2024-7075 sheets joined by friction stir welding," J. Mater. Process. Technol., vol. 206, no. 1–3, pp. 249–255, Sep. 2008.
17. H. Jamshidi Aval, S. Serajzadeh, and A. H. Kokabi, "Evolution of microstructures and mechanical properties in similar and dissimilar friction stir welding of AA5086 and AA6061," Mater. Sci. Eng. A, vol. 528, no. 28, pp. 8071–8083, Oct. 2011.
18. A. Scialpi, M. De Giorgi, L. A. C. De Filippis, R. Nobile, and F. W. Panella, "Mechanical analysis of ultra-thin friction stir welding joined sheets with dissimilar and similar materials," Mater. Des., vol. 29, no. 5, pp. 928–936, Jan. 2008.
19. D. Liu, H. Nishio, and K. Nakata, "Anisotropic property of material arrangement in friction stir welding of dissimilar Mg alloys," Mater. Des., vol. 32, no. 10, pp. 4818–4824, Dec. 2011.
20. E. D. Nicholas and W. M. Thomas, "A review of friction processes for aerospace applications," Int. J. Mater. Prod. Technol., vol. 13, pp. 45–55, 1998.
21. P. Vilaça, J. Gandra, and C. Vidal, "Chapter 7 - Linear Friction Based Processing Technologies for Aluminum Alloys : Surfacing , Stir Welding and Stir Channeling," in in Aluminium Alloys - New Trends in Fabrication and Applications, 2012, pp. 159–197.
22. V.I. Vitanov, N. Javaid, and D.J. Stephenson, "Application of response surface methodology

for the optimisation of micro friction surfacing process," Surf. Coatings Technol., vol. 204, no. 21–22, pp. 3501–3508, Aug. 2010.

23. M. L. Kramer de Macedo, G. A. Pinheiro, J. F. dos Santos, and T. R. Strohaecker, "Deposit by friction surfacing and its applications," Weld. Int., vol. 24, no. 6, pp. 422–431, Jun. 2010.
24. R. Puli and G. D. Janaki Ram, "Microstructures and properties of friction surfaced coatings in AISI 440C martensitic stainless steel," Surf. Coatings Technol., vol. 207, pp. 310–318, Aug. 2012.
25. S. Hanke, A. Fischer, M. Beyer, and J. dos Santos, "Cavitation erosion of NiAl-bronze layers generated by friction surfacing," Wear, vol. 273, no. 1, pp. 32–37, Nov. 2011.
26. D. Govardhan, a. C.S. Kumar, K.G.K. Murti, and G. Madhusudhan Reddy, "Characterization of austenitic stainless steel friction surfaced deposit over low carbon steel," Mater. Des., vol. 36, pp. 206–214, Apr. 2012.
27. N. Balasubramanian, R. S. Mishra, and K. Krishnamurthy, "Friction stir channeling: Characterization of the channels," J. Mater. Process. Technol., vol. 209, no. 8, pp. 3696–3704, Apr. 2009.
28. P. Vilaça and C. Vidal, "Ferramenta Modular Ajustável e Respectivo Processo de Abertura de Canais Internos Contínuos em Componentes Maciços (Modular adjustable tool and correspondent process for opening continuous internal channels in solid components)," National patent pending N.o 105628 T, 2011.
29. P. Vilaça, "Fundamentos do processo de soldadura por fricção linear – Análise experimental e modelação analítica," Instituto Superior Técnico, 2003.
30. P. K. Tipaji, "E-Design Tools for Fraction Stir Welding: Cost Estimation Tool," Thesis for Master Degree, University of Missouri-Rolla, 2007.
31. J. Gandra, R. M. Miranda, and P. Vilaça, "Effect of overlapping direction in multipass friction stir processing," Mater. Sci. Eng. A, vol. 528, no. 16–17, pp. 5592–5599, Jun. 2011.
32. J. Gandra, D. Pereira, R.M. Miranda, R.J.C. Silva, and P. Vilaça, "Deposition of AA6082-T6 over AA2024-T3 by friction surfacing - Mechanical and wear characterization," Surf. Coatings Technol., vol. 223, pp. 32–40, May 2013.