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ORIGINAL ARTICLE

A novel friction stir welding robotic platform: welding polymeric materials

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Abstract The relevance, importance and presence of industrial robots in manufacturing have increased over the years, with applications in diverse new and nontraditional manufacturing processes. This paper presents the complete concept and design of a novel friction stir welding (FSW) robotic platform for welding polymeric materials. It was conceived to have a number of advantages over common FSW machines: it is more flexible, cheaper, easier and faster to setup and easier to programme. The platform is composed by three major groups of hardware: a robotic manipulator, a FSW tool and a system that links the manipulator wrist to the FSW tool (support of the FSW tool). This system is also responsible for supporting a force/torque (F/T) sensor and a servo motor that transmits motion to the tool. During the process, a hybrid force/motion control system adjusts the robot trajectories to keep a given contact force between the tool and the welding surface. The platform is tested and optimized in the process of welding acrylonitrile butadiene styrene (ABS) plates. Experimental tests proved the versatility and validity of the proposed solution.

Keywords Friction stir welding · Robotics · Polymers · Force/motion control · ABS · Manufacturing

1 Introduction

The promotion of manufacturing activities is probably one of the most effective ways to encourage economic growth and jobs creation. The question is how to do that? How manufacturing companies in developed countries can compete with low salaries? Much has been discussed around this over the years. However, there seems to be a consensus on the need to make manufacturing companies more flexible, producing what the market needs (small-series and customized products) and less dependent on the cost of labour.

Industrial robots are key elements in flexible manufacturing [1]. The problem is that they are relatively complex machines that need to be reprogrammed to perform a new task. Generally, industrial robots operate in very structured environments, without the capacity to adapt to dynamic scenarios. Thus, there is much research work to do in several different areas related to robotics, for example, in human-robot interaction and robot autonomy. At the same time, the application of robots in new and nontraditional manufacturing processes is another area for further research. This paper introduces and presents the concept and design of a novel friction stir welding (FSW) robotic platform for welding polymeric materials.

FSW was initially developed in the early 1990s for joining soft metals [2]. The welded seams produced by this method are free from defects: cracks, shrinkage and porosity. It also produces low distortion, which is a typical difficulty in fusion welding processes. This makes FSW a very attractive welding process. The traditional FSW process consists of a rotational tool, formed by a pin and a shoulder, which is inserted into the abutting surfaces of pieces to be welded and moved along the weld joint (Fig. 1). During the process, the pin is located inside the weld joint, softening the materials and enabling plastic flow as well as mixing materials. The shoulder is placed on the surface of the seam to create a smooth surface. Although this process is mainly applied to butt weld joints, other joint geometries can be welded. Aluminium, cooper, plastics, composites and dissimilar materials (for example, aluminium and cooper) are examples of materials that can be welded by FSW [3, 4]. The applications are many, but the following industries

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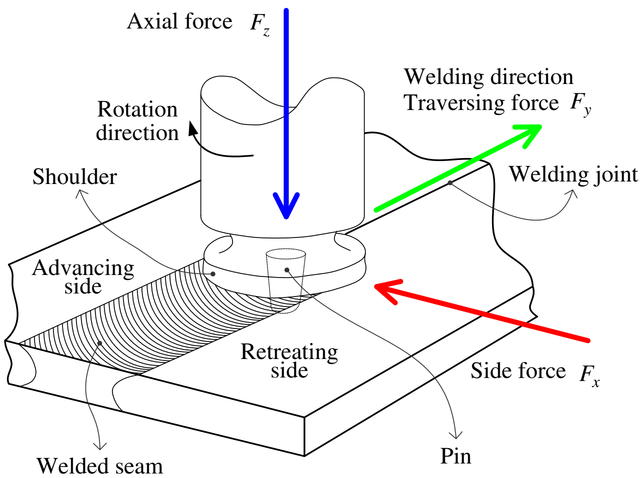

Fig. 1 FSW process

are the most relevant: aerospace, aeronautics, shipbuilding, railway and automotive [5, 6].

The FSW process can be performed using the following equipment: milling machines, FSW machines, parallel robots [7] and anthropomorphic robots [8]. Each of this equipment has its own advantages and disadvantages. They differ in payload capacity, stiffness, workspace, cost, control, etc. [9]. Table 1 resumes the main features of each kind of equipment. Summarizing, it can be stated that the anthropomorphic robots have some important advantages over the other equipment: flexibility, economically competitive, large workspace, fast setup, diverse programming options and capacity to perform multidirectional welds [6]. On the other hand, it presents some relative disadvantages: the reduced stiffness of the robotic arm in the context of the high forces involved into the process and the positional error associated to this kind of machine (clearance in motor and geared transmission mechanisms, backlash, bearing run-out, vibration, etc.) [10–13].

The number of studies in the field of robotic FSW is relatively low but with promising results. Robot prototypes for robotic FSW have been developed, and there are already some solutions in the market [14]. The main problems in using robots performing FSW (reduced stiffness and positional error) and future research directions are discussed in [15, 16]. According to the current state of the art, there are four different ways to control the robotic FSW process:

- Adjusting the plunge depth according to a given set force;
- Adjusting the plunge depth according to a given set torque for the tool;
- Adjusting the plunge depth according to a given set torque for the robot motors;
- Adjusting the traverse speed according to a given set force.

There are a number of approaches to force/motion control applied to robotic FSW [17–20]. The influence of the torque parameter on the control of the FSW process has been studied [21]. An interesting study in the field is dedicated to the development of a CNC milling machine with an integrated force control system. The quantity of heat transferred to the process is controlled through the traverse speed of the tool. It also presented a study in which the force control system (axial force) is linked to the penetration of the tool. These two methods are compared [22]. Another study presents the design and implementation of a FSW force controller [23]. A feedback controller for the path force is designed using the polynomial pole placement technique. The controller is implemented in a Smith predictor-corrector structure to compensate for the inherent equipment communication delay. It is shown that wormhole generation during the welding process is eliminated. Sensory feedback has been used to perform tool trajectory adjustments in welding aluminium plates [24]. Results are compared with the ones produced by a milling machine. The effect of the stiffness of the robot in trajectory compensation (tool deviations) has also been a subject of study [25].

Simulation plays an important role in the development of some controllers for FSW. Robot controller's performance has

Table 1 FSW equipment features

Characteristics ↓	Equipment			
	Milling machine	FSW machine	Parallel robot	Anthropomorphic robot
Flexibility	Low	Low/medium	High	High
Cost	Medium	High	High	Low
Stiffness	High	High	High	Low
Working volume	Medium	Medium	Low	High
Setup time	Low	High	Medium	Medium
Number of programming options	Low	Medium	High	High
Capacity to produce complex welds	Low	Medium	High	High
Control type	Motion	Motion/force	Motion	Motion

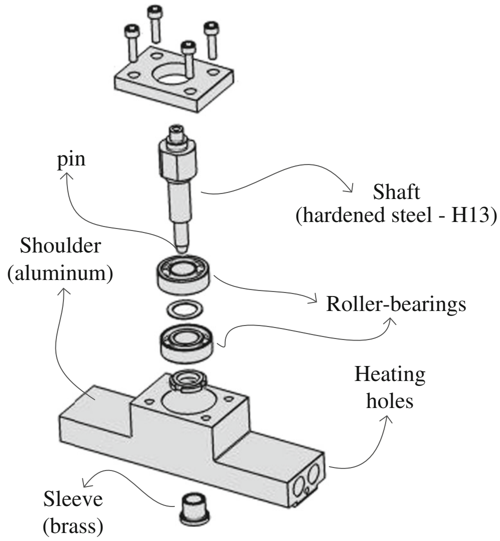

Fig. 2 FSW tool

been tested in simulation environments for the process of FSW. This allows the observation of the controller's behaviour in the presence of perturbations such as tool oscillation and lateral/rotational deviations [26]. Numerical simulation tools have been applied to analyse different FSW parameters [27]. It was achieved that the rotational speed of the tool and the axial force affect mutually the quality of welding [28]. These results have already been proved by real experiments [29].

The FSW process is defined by a number of parameters that influence the robotic process [8, 30–32]. These parameters are rotational speed, traverse speed, axial force, plunge depth, tool geometry, external heating (when used) and dwell time, among others. The investigation of the relationship between the plunge depth and the corresponding axial force is a factor of major importance. Problems in the force controller stability could be caused by the transient response characteristics at the beginning of the welding stage [33]. Some authors have studied the application of seam tracking with base on measured axial forces from the FSW process in order to improve the quality of the welds [34, 35].

In view of the above, it can be seen that a major challenge that hinders further diffusion of robotic FSW is the high forces involved in the process [36]. Nevertheless, force and motion control can attenuate this situation so that since 2000 that anthropomorphic robot is used in FSW [18]. Researchers and engineers rapidly realized that an appropriate robotic system is able to perform FSW with all the advantages highlighted before.

Since robotic FSW is not fully developed yet, there is a lot of room for improvements. In this paper, we concentrate on the concept and design of a novel FSW robotic platform for welding polymeric materials. The platform is composed by three major groups of hardware: a robotic manipulator, a FSW tool and a support for the FSW tool. This last element is also responsible for supporting a force/torque (F/T) sensor and a servo motor that transmits motion to the FSW tool.

During the welding process, a hybrid force/motion control system adjusts the robot trajectories (plunge depth) to keep a given contact force between the tool and the welding surface. The controller has as input the contact forces between the tool and the workpiece in each instant of time. The platform is tested and optimized in the process of welding acrylonitrile butadiene styrene (ABS) plates. Experimental tests proved the versatility and validity of the solution.

2 Concept and design

The main goal of this research was to develop a versatile FSW robotic platform capable to produce quality welds in terms of surface appearance. Thus, in order to support the definition of

Fig. 3 Robotic FSW platform

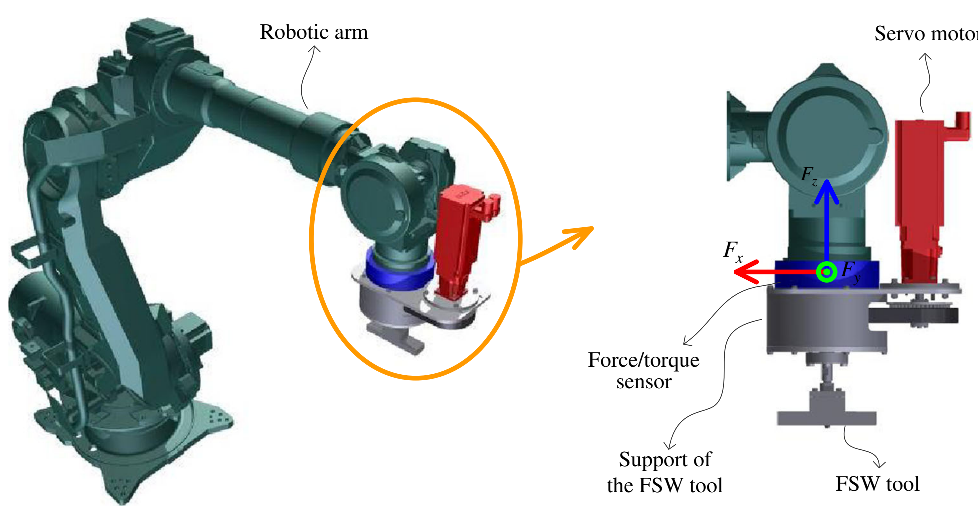

Table 2 FSW parameters threshold

Parameter	Threshold value
Axial force (F_z)	4,000 N
ABS plates thickness	6 mm
Tool rotational speed	1,500 rpm
Traverse and side force $\left(\sqrt{F_x^2 + F_y^2}\right)$	2,000 N
Torque (M)	4 Nm

the concept, it established a set of features that the platform should have:

- Flexibility;
- Robustness;
- Simplicity;
- Easy to programme;
- Adaptability to different force conditions;
- Capability to weld different materials;
- Low setup time;
- Capability to use different tools;
- Easy to tune (change of rotational speed, traverse speed, set forces and set temperature);
- Cheaper than FSW machines;
- Low weight.

The manipulator used is a 6 degrees of freedom (DOF) anthropomorphic robot. The traditional FSW tool (Fig. 1) does not give proper results in terms of weld morphology and tensile strength when applied to polymeric materials. This effect is caused by specific properties of polymeric

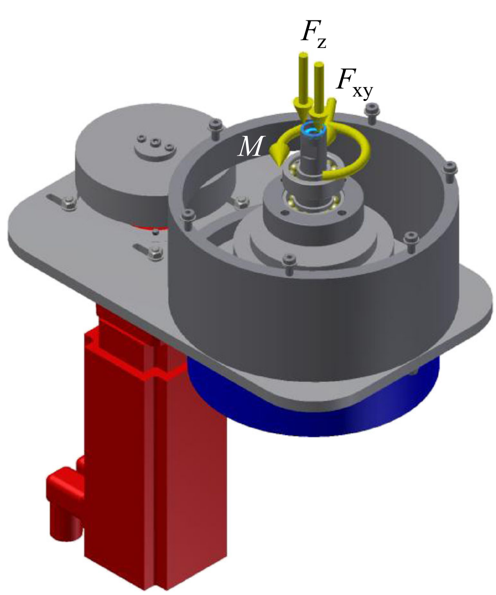

Fig. 4 Major loads acting on the system

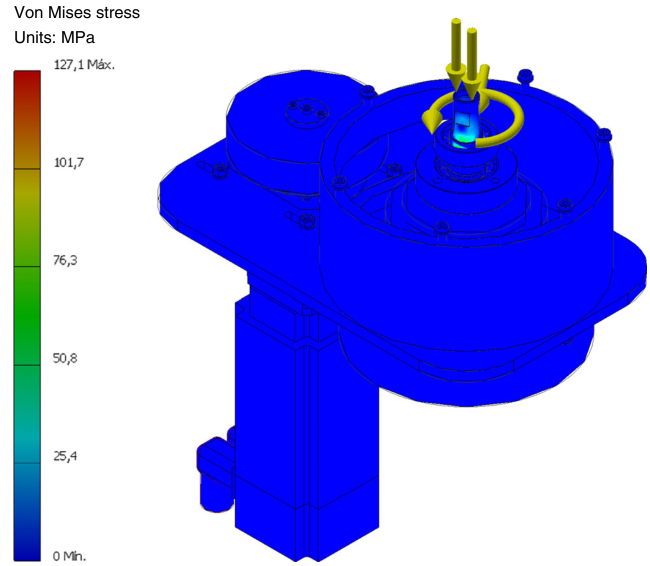

Fig. 5 Stress obtained by FEA

materials, such as their low melting temperature and low thermal conductivity when compared to metals. The FSW tool was developed with base on previous studies in the field [37] and optimized by trial and error in experimental tests carried out in a FSW machine in the process of welding polymers (Fig. 2) [29]. This tool consists of a stationary shoulder and a conical threaded pin of 5.9 mm length and 10 and 6 mm in diameter, at the base and at the tip of the pin, respectively. A long stationary shoulder was designed in order to allow heating in front of and behind the pin. Furthermore, as in injection moulding of polymers, where during the cooling a minimum threshold of pressure is needed to avoid shrinkage and porosity formation, in FSW of polymers, a minimum

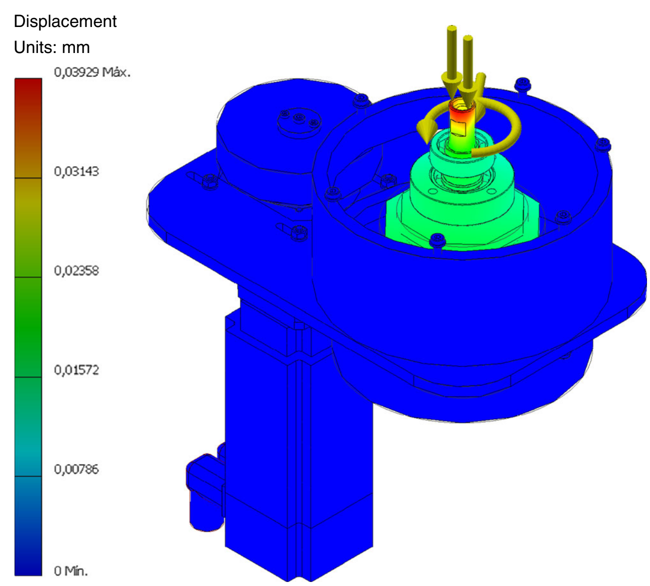

Fig. 6 Displacement obtained by FEA

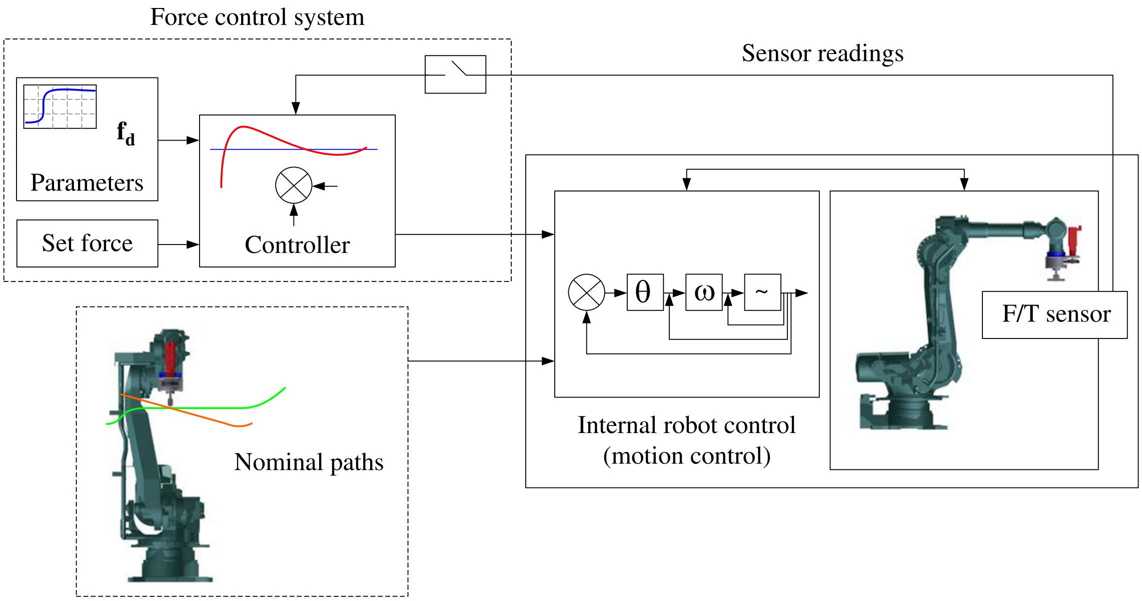

Fig. 7 Control overview of the robotic FSW platform

threshold of axial force is needed to avoid the same defects and improve the mixing of material. This role is played by the long shoulder. Based on previous studies it was decided that the static shoulder must be allowed to move/adapt (during the translation movement of the tool) by itself. In this way, it would be to avoid unnecessary friction, and consequently, loads, inside the tool. Thus, the FSW tool would have a longer life and the required power of the servomotor would be lower. This choice had the disadvantage of requiring an additional support guide to restrict the rotational movement of the shoulder.

This study focuses mainly on the definition of the concept and design of the support of the FSW tool. In terms of concept, it has to have the following functionalities:

– Support the axial forces generated during the process, so that the tool moves in harmony with the robot wrist;
– Transmit power (rotation motion) from the servomotor to the tool;
– Measure forces and torques generated by the welding process (this is necessary for the force/motion control process).

Figure 3 shows the concept. It can be seen that it was decided to align the sixth axis of the robot and the F/T sensor with the FSW tool axis in order to avoid unnecessary shear stress. Rotation motion from the servo motor is transmitted to the tool by means of a belt with a gear ratio $i=1$.

In terms of mechanical design, the first step was to establish an operating range for the platform according to previous experience and related studies in the field [29–32]. Thus, different threshold values for different parameters were defined (Table 2). The loads acting on the system during the welding process are schematically represented in Fig. 4.

The system design was optimized and validated using finite element analysis (FEA) and considering the loads in Fig. 4 with a factor of safety of 2.5. This optimization was necessary in order to ensure that the solution is mechanically robust without being oversized. Autodesk Simulation was used as FEA software, and the results were obtained with a mesh automatically generated by the software. Figure 5 shows the stress obtained by FEA in which we can see a maximum value of 127 MPa. Since the material is steel with a yield strength of 207 MPa it can be concluded that the system is well designed and has capacity to support the loads involved in the process. Figure 6 shows the maximum displacement obtained by FEA, 0.039 mm, an acceptable value for this kind of equipment.

3 Hybrid force/motion control

As previously mentioned, robotic FSW solutions need force/motion control to produce the desired weld quality. In this

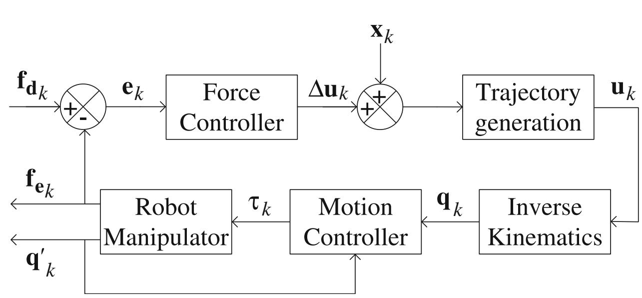

Fig. 8 Hybrid force/motion control system

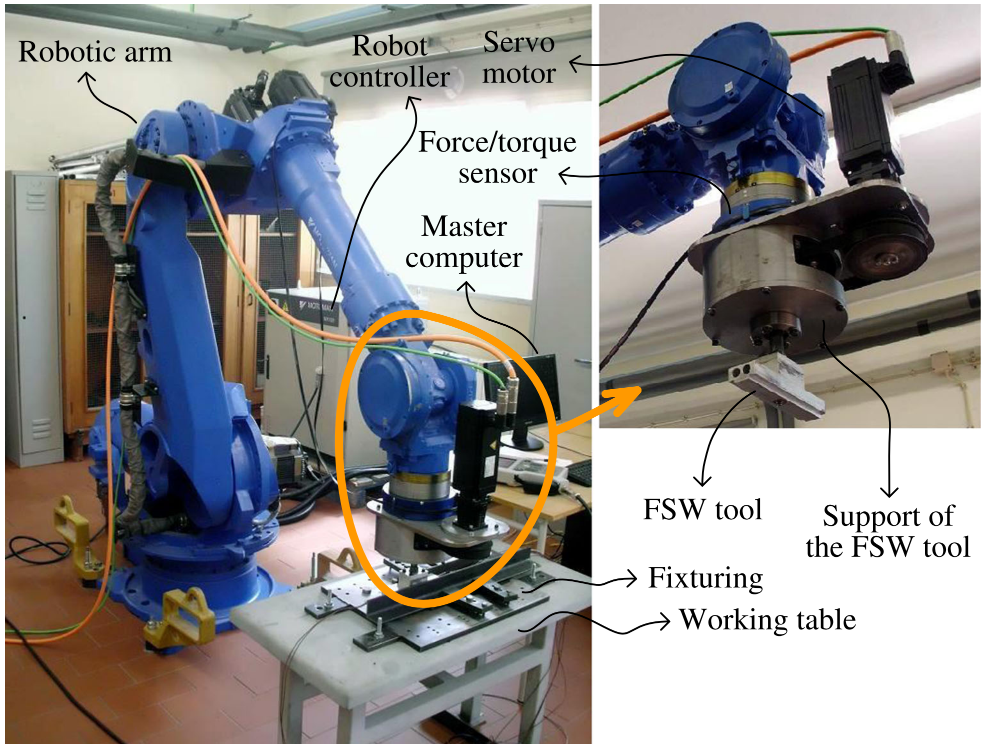

Fig. 9 Hybrid force/motion control system

paper, we are proposing to adjust the plunge depth according to a set axial force. In previous studies, two control methodologies were tested, using a PI and a Fuzzy-PI controller [38, 39]. These controllers showed different behaviours; essentially, the Fuzzy-PI converges faster than the PI controller. On the other hand, the PI controller provides less fluctuation but at the beginning of the process, it has a large overshoot. Figure 7 shows a general control overview of the robotic FSW platform. The process starts with the definition of the nominal robot paths that will be adjusted according to the forces being exerted on the tool during the process [39]. The robot is preprogrammed (nominal paths) by off-line programming as described in previous studies in which target points are extracted from CAD [40]. In order to integrate the force control loop with the motion control loop, the methods presented in [39] are implemented. During the welding process, the forces and torques measured by the F/T sensor and the current pose of the robot end-effector serve as input to the force/motion control system that outputs adjustments for the nominal path. This is done to keep a given set force between the tool and the welding surface. Figure 8 shows the controller in more detail, in which τ is the vector of applied joint torques, q is the vector of joint positions, q' is the vector of actual joint positions, Δu is the vector of correction of displacements and orientations in Cartesian space (plunge depth adjustment), u is the robot displacement in Cartesian space, x is the nominal path, f_d is the desired force (set force) and f_e is the actual force. In addition, the system has incorporated an independent external temperature control system to keep the tool temperature with a desired set value.

4 Implementation

Figure 9 shows the real platform, and Table 3 lists the diverse hardware components applied into the construction of the platform. The servo motor has a maximum rotational speed of 1,500 rpm, a torque of 5.3 Nm and weight of 7 kg (this is a low weight solution). The F/T sensor has a load capacity of 4,000 N along z axis, 2,000 N along x and y axes and a torque of 400 Nm. The robot has a payload of 165 kg and 6 DOF.

Table 3 Hardware components model

Component	Model
Servo motor	SEW PSF221 CMP63M/KY/RH1M/SM1
Servo drive (motor)	MDX61B0014-5A3-4-00/DER11B
F/T sensor	JR3 75E20A-I125-D
Robotic arm	Motoman ES165N
Robot controller	Motoman NX100
Temperature controller	Delta DTD 48
Temperature sensor	Thermocouple J type
Resistances	Resistances of 400 W

Table 4 Parameters used in the welds

Parameter	Weld 1	Weld 2	Weld 3	Weld 4
Type of machine	Robot	Robot	Robot	FSW machine
Set axial force (N)	1,500	Not applied	1,500	1,500
Traverse speed (mm/s)	3.3	3.3	1.6	1.6
Rotational speed (rpm)	1,000	1,000	1,500	1,500
Set temperature (°C)	115	115	115	115

5 Experimental tests and results

Experimental tests were carried out in the process of joining two ABS plates. Butt welds were produced between ABS plates of 300×80×6 mm^3. The robot is preprogrammed (nominal path) to move the FSW tool linearly along the welding joint. At first, it was necessary to perform some tests to establish what ranges of parameters (control parameters and set temperature) lead to better welds. This is done by trial and error and through visual analysis of the welded seams as well as the analysis of the behaviour of the control system. The ranges for the other parameters (axial force, traverse speed and rotational speed) were analysed and defined in previous studies [29]. From a set of welding tests, four representative tests were chosen to be presented in this manuscript (weld 1, weld 2, weld 3 and weld 4). These tests were performed in the robotic system presented in this manuscript and in a FSW machine with the parameters presented in Table 4. Figure 10 shows a welding being performed in the robotic system.

Figures 11, 12, 13 and 14 show the results of the tests weld 1, weld 2, weld 3 and weld 4, respectively. A visual analysis indicates that Weld 1 presents an acceptable level of quality. In the context of this study, the welded seam quality depends on the following factors:

– Smoothness of the crown seam;
– Quantity of pores or holes in the crown seam;
– Degradation of base material.

In terms of loads applied in the process, after an initial period in which the axial force F_z reaches −1,744 N, it converges to the set force of −1,500 N. It observed a large overshoot which is due to the high weight of the integrative parameter. The value of this parameter is relatively high in order to eliminate any offset. A similar reasoning can be done for the adjustment of the plunge depth Δu. Actually, as shown

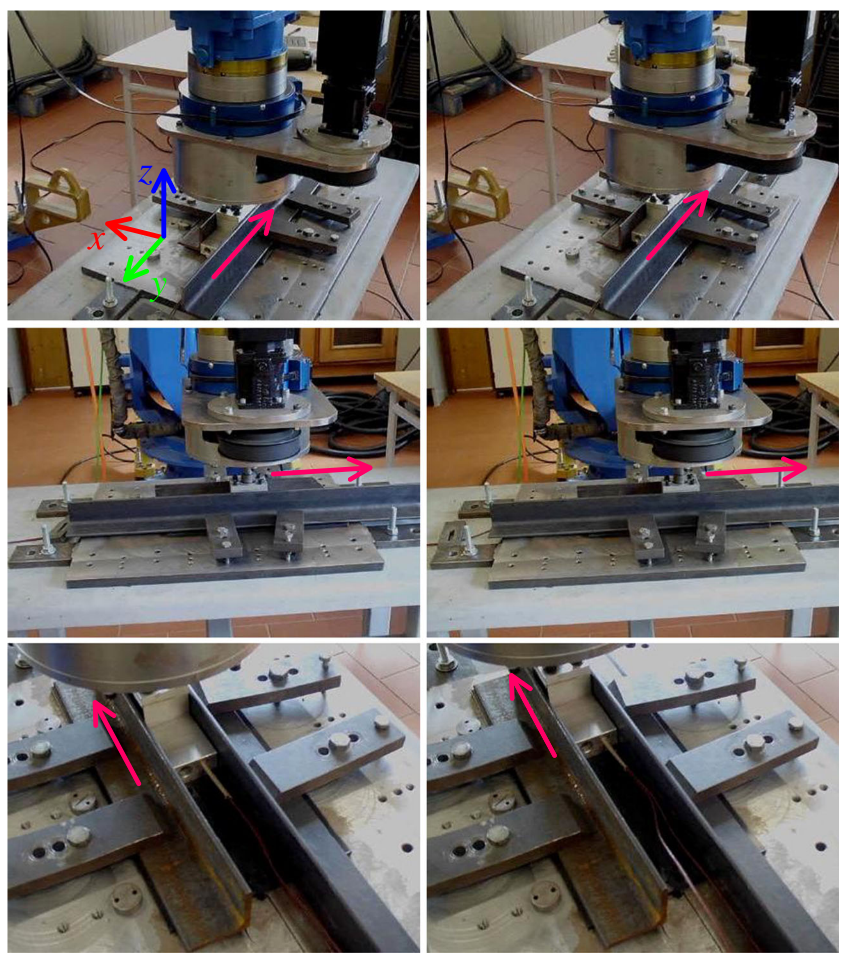

Fig. 10 Experimental tests being performed

in Fig. 11, the adjustment of the plunge depth reached over 3.4 mm. However, these 3.4 mm are not real and are dependent on the inaccuracy of the robot, workpiece deflection and programming error (off-line). In the beginning of the process, the shoulder is not in contact with the upper surface of the workpiece because, as mentioned above, when the robot is programmed in relative coordinates, there are usually positional inaccuracies. Furthermore, by the same reason when a displacement of 3.4 mm is asked to be performed by the robot, the robot does not perform the 3.4 mm exactly. It performs a different quantity which depends on the robot and environment characteristics. The performed displacement quantity is usually lower than the asked quantity [10–13]. It can be observed in Fig. 11 that the output F_z presents a low fluctuation around the set point (less than 5 N) and no offset. This fluctuation comes from noise and some disturbances generated in the robot joints. Since the plates are perfectly flat, they do not introduce disturbances in the system.

As a means of comparison, it was performed a test (weld 2) with no force control, just moving the robot tool linearly along the welding joint according to the parameters in Table 4. From Fig. 12, it can be concluded that the axial force is not enough to compress the melted plastic, producing a welded seam without the desired quality. The welded seam is rough and has an external cavity in almost whole of its depth. Thus, there is a material that was thrown out of the welding joint, and the joining is only established on the root of the seam. The cause of this phenomenon is the existence of a little gap between the shoulder and the welding joint; hence, part of the tool pin volume is out of the welding joint. This leads to less heat generation by friction and hinders heat transfer by conduction between the heating system and the welding joint. Thus, the material of the welding joint is less heated, which means that we have a traverse force with a higher value than when force/motion control is used. In this scenario, the shoulder does not

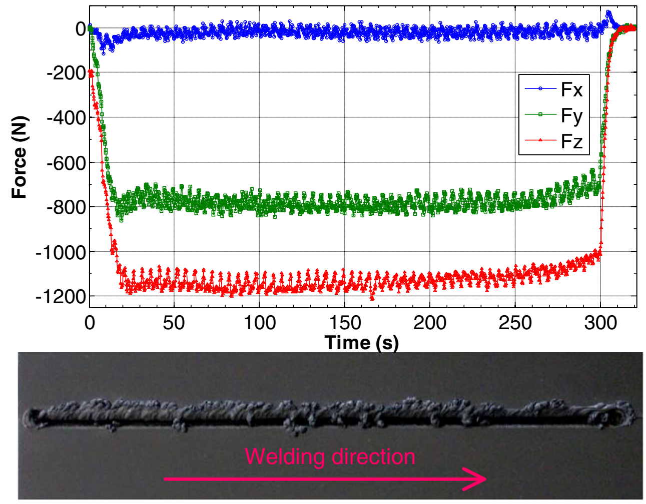

Fig. 12 Resulting weld 2: welded seam and measured loads during robotic FSW process using motion

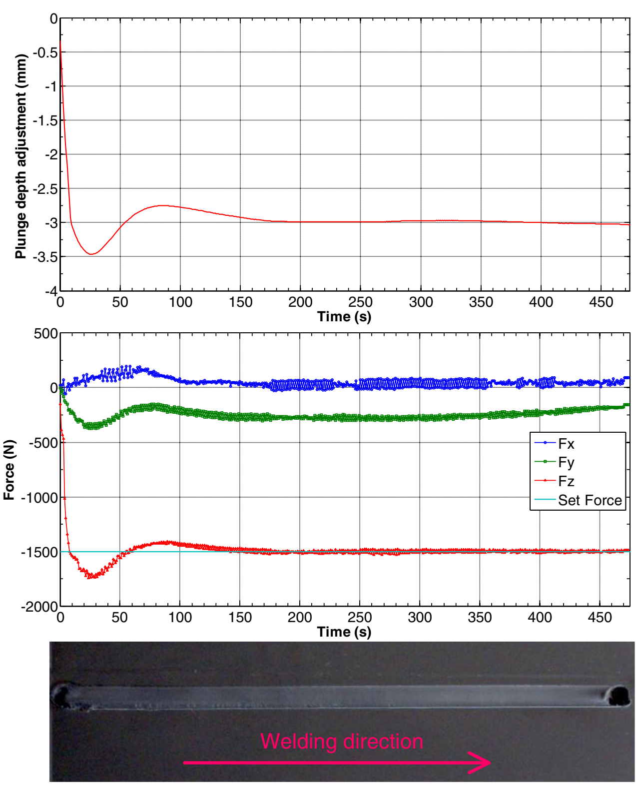

Fig. 11 Resulting weld 1: welded seam, measured loads and plunge depth adjustment during robotic FSW process using force/motion control

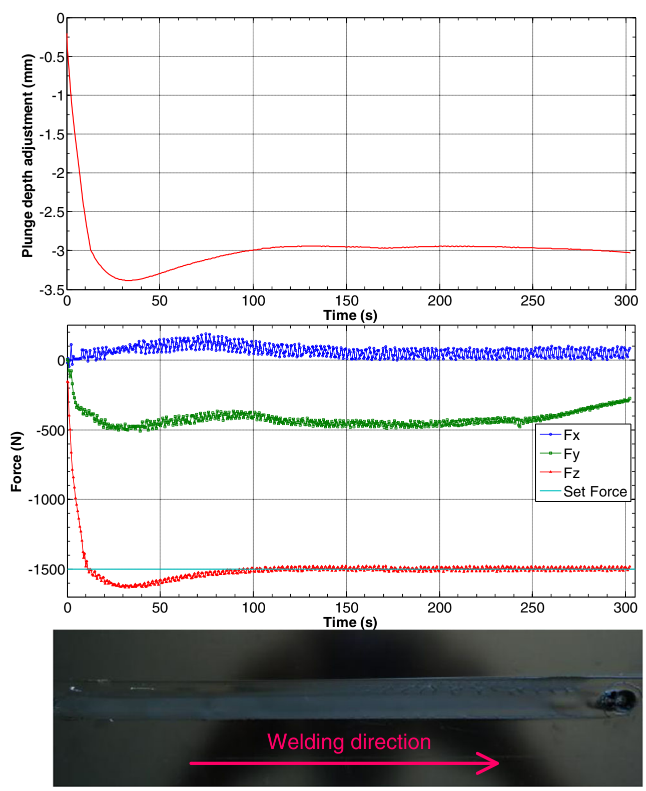

Fig. 13 Resulting weld 3: welded seam, measured loads and plunge depth adjustment during robotic FSW process using force/motion control

Fig. 14 Resulting weld 4: welded seam performed in a FSW machine

serve its purpose which is to serve as constraint to the molten material.

The weld 3 was performed with the same parameters as the weld 4; the only difference is that the weld 3 was performed in the robotic system and the weld 4 was performed in a FSW machine as shown in Table 4. The resulting welds present very good quality. In general, their qualities are very similar since both welds present a smooth and flat surface. The weld 3 is free of pores, and there was not a production (appearance) of burr. This weld just presents superficial degradation on the end part of the weld. This is due to the excessive heat transmitted to the surface. Since the FSW tool has high thermal inertia and the heating system just controls the warming and not the cooling, sometimes, the surface reaches too much high temperatures. The behaviour of the force/motion control system was similar to weld 1 with the difference that in this case, the overshoot was smaller (only about −1,637 N). In this case, the rotational speed was higher and consequently more heat was generated. Weld material was more softened, leading to lower contact force (different behaviour of the plant (FSW tool/ABS plates)). The weld 4 just presents some pores together with some roughness in the beginning of the welded seam in the retreating side which is the weakest side [29]. There was some burr produced in this weld. On the whole, it can be stated that weld 3 is a little better than weld 4.

By the analysis of Figs. 11, 12 and 13, it is possible to conclude that the robotic system is perfectly stable. Because when there is a small or no variation in plunge depth, the measured axial force suffers a very small variation. The global conclusion is that force/motion control improves FSW quality and is a condition to perform robotic FSW.

6 Conclusion and future work

The complete concept and design of a novel FSW robotic platform for welding polymeric materials has been presented. Experimental results demonstrate that it is possible to weld plastics with an acceptable level of quality using a robotic FSW platform aided by force/motion control and tuned with appropriate process parameters. On the other hand, it was concluded that it is virtually impossible to produce quality welded seams without force/motion (for robotic FSW). Robotic FSW has a number of advantages over common FSW machines: it is more flexible, cheaper, easy and fast to setup and easy to programme. Experimental tests proved the versatility and validity of the solution. The proposed platform can be applied to weld other materials just by changing the loads capacity, the tool and the welding parameters. Future work will seek to integrate other parameters (such as traverse speed, rotational speed, temperature and vibration) in the force/motion controller. To reduce the overshoot in the beginning of the weld, it is intended to use different control parameters in the beginning of the weld and when stationary conditions are reached. Development of FSW tools for complex welding in 3D space will be a target for further research. At this moment, the authors are investigating the capacity of the platform in welding dissimilar materials.

References

1. Neto P, Pereira D, Pires JN, Moreira AP (2013) Real-time and continuous hand gesture spotting: an approach based on artificial neural networks. In: Proc 2013 I.E. Int Conf Robotic Automation (ICRA 2013), pp 178-183, Karlsruhe, Germany
2. Thomas WM, Nicholas ED, Needham JC, Church MG, Templesmith P, Dawes CJ (1991) Friction-stir butt welding. GB Patent 9125978.8, UK
3. Lee RT, Liu CT, Chiou YC, Chen HL (2013) Effect of nickel coating on the shear strength of FSW lap joint between Ni-Cu alloy and steel. J Mater Process Technol 213(1):69–74
4. Sonne MR, Tutum CC, Hattel JH, Simar A, Meester B (2013) The effect of hardening laws and thermal softening on modelling residual stresses in FSW of aluminum alloy 2024-T3. J Mater Process Technol 213(3):477–486
5. Mishra RS, Ma ZY (2005) Friction stir welding and processing. Mater Sci Eng R Rep 50:1–78
6. Gibson BT, Lammlein DH, Prater TJ, Longhurst WR, Cox CD, Ballun MC, Dharmaraj KJ, Cook GE, Strauss AM (2013) Friction stir welding: process, automation, and control. J Manuf Process, 2013
7. Fleming PA, Hendricks CE, Cook GE, Wilkes DM, Strauss AM, Lammlein DH (2010) Seam-tracking for friction stir welded lap joints. J Mater Eng Perform 19(8):1128–1132
8. Zimmer S (2008) Contribution a l'industrialisation du soudage par friction malaxage. PhD thesis, Arts et Métiers ParisTech, Paris, France
9. Okawa Y, Taniguchi M, Sugii H, Marutani Y (2006) Development of 5-axis friction stir welding system. In: Proc SICE-ICASE Int Joint Conf 2006, pp 1266-1269, Busan, Korea
10. Mustafa SK, Pey YT, Yang G, Chen I (2010) A geometrical approach for online error compensation of industrial manipulator. In: IEEE/ASME Int Conf Adv Intell Mechatron, pp 738-743, Montreal, Canada

11. Heisel U, Richter F, Wurst KH (1997) Thermal behavior of industrial robots and possibilities for errors compensation. CIRP Ann Manuf Technol 46(1):283–286
12. Gong C, Yuan J, Ni J (2000) Nongeometric error identification and compensation for robotic system by inverse calibration. Int J Mach Tool Manuf 40(14):2119–2137
13. Ruderman M, Hoffmann F, Bertram T (2009) Modeling and identification of elastic robot joints with hysteresis and backlash. IEEE Trans Ind Electron 56(10):3840–3847
14. Soron M, Lahti KE (2009) Robotic friction stir welding of complex components using RosioTM. Svetsaren 64(1):13–15
15. Fleming PA, Lammlein D, Wilkes D, Fleming K, Bloodworth T, Cook G, Strauss A, DeLapp D, Lienert T, Bement M, Prater T (2008) In-process gap detection in friction stir welding. Sens Rev 28(1):62–77
16. Yavuz H (2004) Function-oriented design of a friction stir welding robot. J Intell Manuf 15:761–775
17. Soron M, Kalaykov I (2006) A robot prototype for friction stir welding. In: Proc 2006 I.E. Conf Robot Autom Mechatron, pp 1-5
18. Smith CB (2000) Robotic friction stir welding using a standard industrial robot. In: Proc 2nd Int Symp Frict Stir Weld
19. Zhao X, Kalya P, Landers RG, Krishnamurthy K (2007) Design and implementation of a nonlinear axial force controller for friction stir welding processes. In: Proc. 2007 American Contr Conf, pp 5553-5558, New York, USA
20. Longhurst WR (2009) Force control of friction stir welding. PhD thesis, University of Vanderbilt, Nashville, TN
21. Longhurst WR, Strauss AM, Cook GE, Fleming PA (2010) Torque control of friction stir welding for manufacturing and automation. Int J Adv Manuf Technol 51:905–913
22. Longhurst WR, Strauss AM, Cook GE (2010) Enabling automation of friction stir welding: the modulation of weld seam input energy by traverse speed force control. J Dyn Syst Meas Control 132:1–11
23. Zhao X, Kalya P, Landers RG, Krishnamurthy K (2009) Path force control for friction stir welding processes. Air Force Res Lab Rep, AFRL-RX-WP-TP-2009-4127, pp 1-8, Wright-Patterson, USA
24. Marcotte O, Abeele LV (2010) 2D and 3D friction stir welding with articulated robot arm. In: Proc 8th Int Symp Frict Stir Weld 2010. Timmendorfer, Germany, pp 778–797
25. Backer JD, Christiansson AK, Oqueka J, Bolmsjö G (2012) Investigation of path compensation methods for robotic friction stir welding. Ind Robot 39(6):601–608
26. Bres A, Monsarrat B, Dubourg L, Birglen L, Perron C, Jahazi M, Baron L (2010) Simulation of friction stir welding using industrial robots. Ind Robot 37(1):36–50
27. Neto DM, Neto P (2013) Numerical modeling of friction stir welding process: a literature review. Int J Adv Manuf Technol 65(1–4):115–126
28. Crawford R, Cook GE, Strauss AM, Hartman DA (2006) Modelling of friction stir welding for robotic implementation. Int J Model Identif Control 1(1):101–106
29. Mendes N, Loureiro A, Martins C, Neto P, Pires JN (2014) Effect of friction stir welding parameters on morphology and strength of acrylonitrile butadiene styrene plate welds. Mater Des 58:457–464
30. Cook GE, Crawford R, Clark DE, Strauss AM (2004) Robotic friction stir welding. Ind Robot 31(1):55–63
31. Zimmer S, Langlois L, Goussain JC, Martin P, Bigot R (2010) Determining the ability of high payload robot to perform FSW applications. In: Proc 8th Int Symp Frict Stir Weld 2010. Timmendorfer, Germany, pp 755–762
32. Backer JD, Soron M, IIal T, Christiansson AK (2010) Friction stir welding with robot for light weight vehicle design. In: Proc 8th Int Symp Frict Stir Weld 2010, pp 14-24, Timmendorfer, Germany
33. Strombeck A, Shilling C, Santos J (2000) Robotic friction stir welding—tool technology and applications. In: Proc 2nd Frict Stir Weld Int Symp, Gothenburg, Sweden
34. Fleming PA, Hendricks CE, Wilkes DM, Cook GE, Strauss AM (2009) Automatic seam-tracking of friction stir welded T-joints. Int J Manuf Technol 45:490–495
35. Cook G, Smartt H, Mitchell J, Strauss A, Crawford R (2003) Controlling robotic friction stir welding. Weld J 82:28–34
36. Smith CB, Hinrichs JF, Crusan A (2003) Robotic friction stir welding: state of the art. In: Proc 4th Frict Stir Weld Int Symp
37. Strand SR (2004) Effects of friction stir welding on polymer microstructure. MS thesis, Brigham Young University, Provo, UT
38. Mendes N, Neto P, Pires JN, Loureiro A (2013) An optimal fuzzy-PI force/motion controller to increase industrial robot autonomy. Int J Adv Manuf Technol 68(1–4):435–441
39. Mendes N, Neto P, Pires JN, Loureiro A (2013) Discretization and fitting of nominal data for autonomous robots. Expert Syst Appl 40(4):1143–1151. doi:10.1016/j.eswa.2012.08.023
40. Neto P, Mendes N (2013) Direct off-line robot programming via a common CAD package. Robot Auton Syst 61(8):896–910