Robotic Friction Stir Welding Aided by Hybrid Force/Motion Control

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***Abstract*—The relevance and importance of industrial robots in manufacturing has increased over the years, with applications in diverse new and non-traditional manufacturing processes. This paper presents the 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, easy and fast to setup, and easy to program. 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 solution.**

Keywords—robotics; friction stir welding; force control; ABS

I. INTRODUCTION

Friction stir welding (FSW) is a solid-state joining technique that can be applied to a wide range of materials such as metals, plastics, composites and dissimilar materials (for example aluminum and cooper). The most significant advantage of FSW is its ability to weld alloys that are difficult or impossible to weld using fusion welding techniques. The welded seams produced by this process are in general free from defects displaying good mechanical properties and visual appearance. 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. During the process, the pin is located inside the weld joint, softening the material and enabling plastic flow, as well as the mixture of materials. The shoulder is placed on the surface of the seam to create a smooth surface.

The FSW process can be performed using the following equipments: milling machines, FSW machines, parallel robots (tricept) and anthropomorphic robots. Each of these equipments has its own advantages and disadvantages [1]. They differ in payload capacity, stiffness, workspace, cost, control, etc. Summarizing, it can be stated that the anthropomorphic robots have some important advantages over

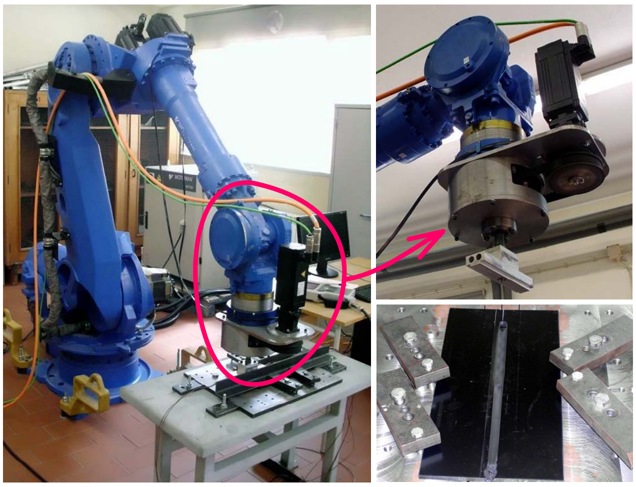

Fig. 1. The experimental FSW robotic platform. A detailed view of the proposed FSW system (top right) and two ABS plates welded by FSW (bottom right).

the other equipment: flexibility, economically competitive, large workspace, fast setup, diverse programming options and capacity to perform multi-directional welds. On the other hand, robotic FSW presents some relative disadvantages: the reduced stiffness of the robotic arm and the necessity to have force/motion control to produce quality welds (as will be proved in this paper).

The number of studies in the field of robotic FSW is relatively low but with promising results. Robot prototypes for robotic FSW of metal materials have been developed and there are already some solutions in the market [2]. The main problems in using robots performing FSW and future research directions are discussed in [3]. 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 [4-5], adjusting the plunge depth according to a given set torque for the tool [6], adjusting the plunge depth according to a given set torque for the robot motors and adjusting the traverse speed according to a given set force [7].

The FSW process is defined by a number of parameters that influence the robotic process of FSW [8]. The investigation of the relationship between the plunge depth and the corresponding axial force is a factor of major importance that

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affects the stiffness of the robot [9]. 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. Nevertheless, force and motion control can attenuate this situation.

This paper introduces and presents the concept and design of a novel friction stir welding (FSW) robotic platform for welding polymeric materials, Fig. 1. The platform is composed by three major groups of hardware: a robotic manipulator, a FSW tool and the support of the FSW tool. This last element is also responsible for supporting the force/torque (F/T) sensor and the 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.

II. 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 the concept, it was established a set of features that the platform should have: flexibility, robustness, simplicity, adaptability to different force conditions, capability to weld different polymeric materials and use different tools, low setup time, easy to tune and cheaper than FSW machines.

The manipulator used is a six degrees of freedom (DOF) anthropomorphic robot that already exists in laboratory. The FSW tool was developed with base on previous studies [10] and optimized by trial and error in experimental tests carried out in a FSW machine welding polymers [11].

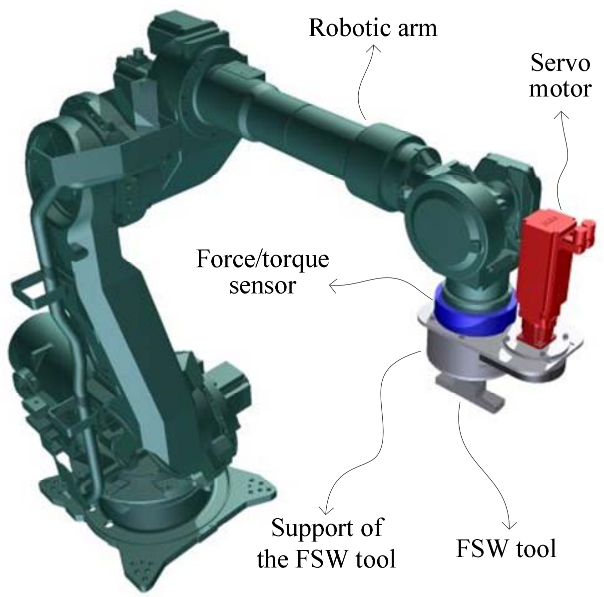

Fig. 2. Robotic FSW platform.

TABLE I. FSW Parameters Threshold

Parameter	Threshold Value
Axial force (F_z)	2000 N
ABS plates thickness	6 mm
Tool rotation speed	1500 rpm
Traverse and side force $\left(\sqrt{F_x^2+F_y^2}\right)$	1000 N
Torque (M)	4 Nm

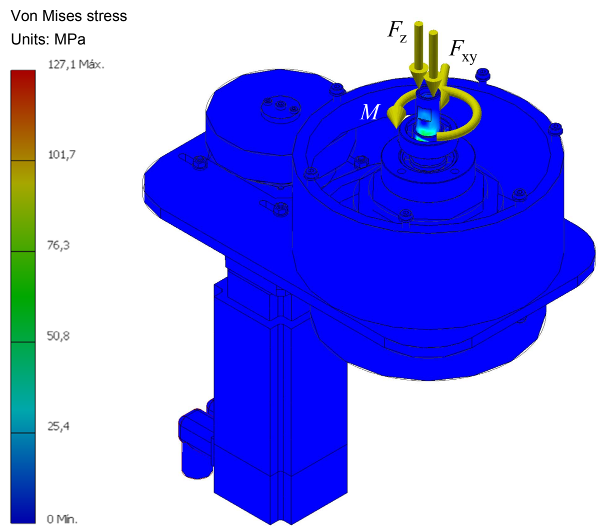

Fig. 3. Stress obtained by FEA.

One of the main goals of this study is the definition of the concept and the 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 servo motor to the tool, measure forces and torques generated by the welding process. Fig. 2 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 different studies in the field [8, 11]. Thus, different threshold values for different parameters were defined, Table I. The forces acting on the system during the welding process are schematically represented in Fig. 3.

The system design was optimized and validated using finite element analysis (FEA) and considering the forces in Fig. 3 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. Fig. 3 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 efforts involved in the process.

III. Hybrid Force/Motion Control

As previously mentioned, robotic FSW solutions need force/motion control to produce the desired weld quality. In this 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 [12-13]. These controllers showed different behaviors, 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 has a large overshoot.

The process starts with the definition of the nominal robot paths that during the process will be adjusted according to the forces being exerted on the tool [13]. 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. Fig. 4 shows the controller with more detail, in which $\boldsymbol{\tau}$ is the vector of applied joint torques, $\mathbf{q}$ is the vector of joint positions, $\mathbf{q'}$ is the vector of actual joint positions, $\Delta\mathbf{u}$ is the vector of correction of displacements in Cartesian space (plunge depth adjustment), $\mathbf{u}$ is the robot displacement in Cartesian space, $\mathbf{x}$ is the nominal path, $\mathbf{f_d}$ is the desired force (set force) and $\mathbf{f_e}$ 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.

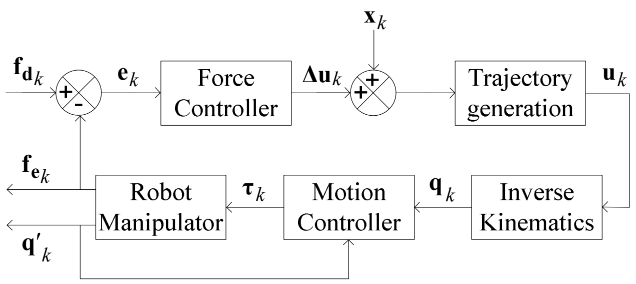

Fig. 4. Hybrid force/motion control system.

IV. Implementation

Fig. 1 shows the real platform and Table II lists the diverse hardware components applied into the construction of the platform. The servo motor has a maximum rotation speed of 1500 rpm and a torque of 5.3 Nm. This choice was due to servo motor provides high torque and has low weight. The F/T sensor has a load capacity of 2200 N along *z* axis, 1100 N along *x* and *y* axes and a torque of 215 Nm. The robot has a payload of 165 kg.

TABLE II. 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

V. Experimental Tests and Results

Experimental tests were carried out in the process of joining two ABS plates with a thickness of 6 mm. The robot is pre-programmed off-line (nominal path) to move the FSW tool linearly along the welding joint [14]. 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 and the behavior of the control system. The ranges for the other parameters (axial force, traverse speed and rotation speed) were analyzed and defined in previous studies [11].

Fig. 5 shows the results of a test performed with the parameters in Table III (experiment 1). A visual analysis indicates that the welded seam presents an acceptable level of quality (no porosities, cracks and shrinkage). In terms of forces, after an initial period in which the axial force F_z reaches a slight overshoot, it converges to the set force (1500 N). A similar reasoning can be made for the adjustment of the plunge depth $\Delta\mathbf{u}$. Fig. 5 shows that the plunge depth reaches about 3.5 mm but this value is not real, it depends on the robot positional accuracy when programmed in relative coordinates, the stiffness of the robot and several mechanical error sources.

As a means of comparison, it was performed a test with no force control, just moving the robot tool linearly along the welding joint according to the parameters in Table III (experiment 2). From Fig. 6 it can be concluded that the axial force is not enough to compress the melted plastic, producing a welded seam without the desired quality. At the same time, since there is a little gap between the shoulder and the welding joint, part of the tool pin volume is out of the welding joint. This gap is due to positional errors which have the same sources as enumerated in experiment 1. This behavior 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.

The global conclusion is that force/motion control is a condition to perform robotic FSW on ABS plates.

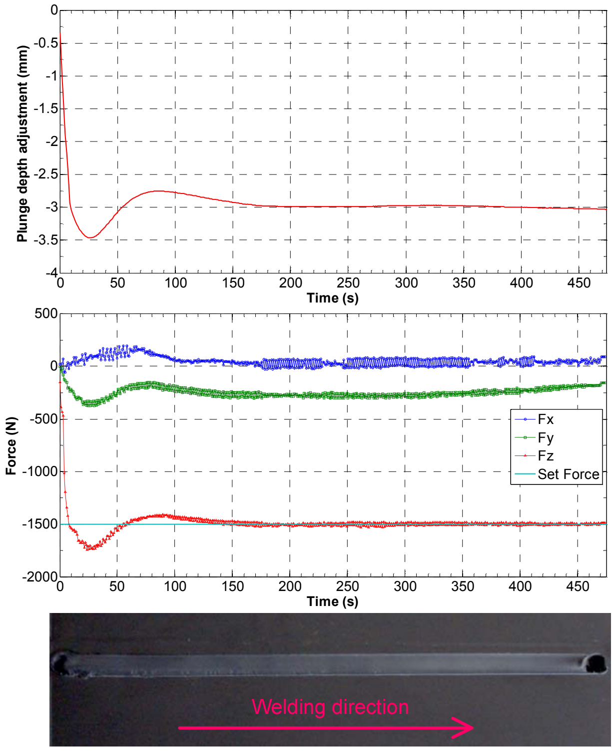

Fig. 5. Welded seam, measured forces and plunge depth adjustment during robotic FSW process using force/motion control.

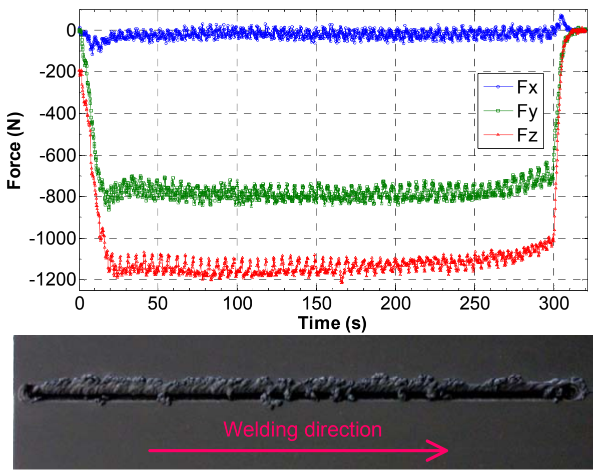

Fig. 6. Welded seam and measured forces during robotic FSW process using motion control.

TABLE III. PARAMETERS VALUES

Parameter	Experiment 1	Experiment 2
Set axial force	1500 N	Not applied
Traverse speed	3.3 mm/s	3.3 mm/s
Rotation speed	1000 rpm	1000 rpm
Set temperature	115 ºC	115 ºC

VI. CONCLUSION

The 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 control (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 program. Experimental tests proved the versatility and validity of the solution. The proposed platform can be applied to weld other materials just by changing the forces capacity, the tool and the welding parameters.

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