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Full length Article

Impact & improvement of tool deviation in friction stir welding: Weld quality & real-time compensation on an industrial robot ☆

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ABSTRACT

The present study proposes the use of an industrial serial robot to reduce the investment cost and to increase the process flexibility of Friction Stir Welding (FSW). The first part of the study characterizes the impact of pin axis position on FS Weld (FSWed) quality. The second part shows a method to compensate the lateral pin deviation in real-time during Robotic Friction Stir Welding (RFSW). This paper shows that a robot with an embedded real-time algorithm for the compensation of the lateral tool deviation can reproduce the same FSWed quality as a gantry-type CNC system. The elastostatic model of an industrial robot is carried out by the classical identification technique and this is embedded in the robot controller. Based on force measurements along the welding process, the corrected path is calculated in real-time.

1. Introduction

FSW is an emerging manufacturing technology for aerospace, automotive, railway and civil structures. It offers ways of designing lighter structures at lower manufacturing cost than traditional joining methods: fusion welding, riveting or adhesive bonding [1,2]. As illustrated in Fig. 1, FSW process involves a rotating tool consisting of a pin and a shoulder.

The pin is inserted between adjoining metal pieces and the shoulder is placed at the top surface of the joint. The heat generated by the tool friction brings the metal to a viscoplastic state, while the pin stirs the two pieces together. Severe plastic deformation, and flow of this plasticised metal occurs as the tool is translated along the welding direction. Material is transported from the front of the pin to the trailing edge where it is forged into a sound and homogenous joint. Since the invention of FSW in 1991 by The Welding Institute (TWI), many studies have demonstrated its capability for joining a wide range of materials. Unlike fusion welding, the melting point of the welded materials is not reached during FSW. This reduces the probability of distortion, porosity and loss of mechanical properties of weldments. Moreover, the technology can be applied to hot cracking sensitive aluminium alloys, such as 2xxx [3,4] and 7xxx series [5], which are considered to be difficult to weld by using traditional processes. However, the FSW manufacturing parameters impact significantly the weld quality. Therefore, the tool weld speed, the rotationnal speed [6–8] and the pin position in the weldment [9] have to be carefully selected and controlled. These welding parameters have important effects on material properties, such as the metallurgical microstructure, defects (porosity, lack of penetration), hardness, electric conductivity and tensile strength. Currently, gantry-type CNC systems are being used for FSW manufacturing. These machines offer a high stiffness and can tolerate the high forces during FSW in order to produce a good weld quality. For 10 years [10–14] an effort is done to replace dedicated gantry-type machines with industrial serial robots to reduce the investment cost and to increase the process flexibility. However, two limitations of RFSW can be highlighted. The first one is the payload capability of industrial robots which limits the welding thickness up to 8 mm for aluminium materials (AW-5083-H111, AW-6060-T66, AC-46000) [15]. The second limitation is the low stiffness of the robotic joints and, thus, the important elasticity of serial robots [16–19]. Consequently, the robot deformations under the high process forces cause both axial and lateral FSW tool deviations (about several millimeters) [20,21], impacting the weld quality. Axial tool

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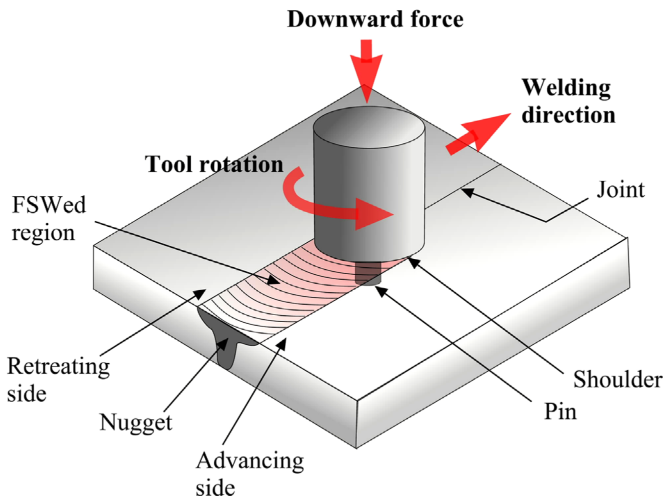

Fig. 1. Description of the FSW process.

deviation is currently compensated by the well-documented force control approach [22,13,23]. However, for butt joint configuration, the lateral deviation can modify the position of pin axis and cause lack-of-penetration defects reducing significantly the mechanical resistance of FSW weldments [9]. In RFSW, the lateral deviation is not measured by the robot joint encoders and is uncontrolled as it depends on the process loads and robot configurations [24]. The first part of the paper characterizes the impact of pin axis position on FSWed quality, especially on the appearance of lack-of-penetration defect, and on the tensile strength properties. This experiment is carried out on a gantry-type CNC system in order to use a high stiffness machine and to control accurately the pin position. The second part shows a method to compensate the lateral deviation in real-time during RFSW and the associated improvements on the weld quality. A real-time algorithm embedded in the industrial robot controller calculates the lateral deviation based on the FSW force measurements and the knowledge of the elastic robot structure.

2. Experimental set up

FSW of AA 5754-H22 sheets is performed using coupons of 300-mm long by 100-mm wide by 3 mm thick in butt configuration as shown in Fig. 2. The rolling direction of the coupons is placed parallel to the welding path. Samples are positioned on a steel backing anvil and clamped along the two long edges.

FSW trials are carried out on a Vernier CNC system in the first part of the study as shown in Fig. 3. In the second part of the study, RFSW experiments are performed on a test-bed incorporating a FANUC S900iB/400 RJ3iB industrial robot and an electrically driven process end-effector as shown in Fig. 4. The payload capability of this robot is 400 kg, with a maximum reach of 2488 mm and a repeatability of $\pm$ 0.5 mm.

As shown in Fig. 5, weldments are produced with a FSW tool made of H13 tool steel and composed of a pin and a shoulder. The pin is a conical left-hand threaded pin of 3-mm diameter and 2.8-mm long. The shoulder is a scroll shape with a diameter of 8.5 mm.

The welding parameters consist in a rotational speed of 1200 RPM, a traveling speed of 6 mm/s and a tilt angle of 0° as illustrated in Fig. 6. During the trials on the CNC system, position control welding mode is used with a fixed shoulder penetration of 0.1-mm depth. For RFSW experiments, force control welding mode is activated to produce samples (a vertical forge force of 3.1 kN). In FSW mass production, the force control mode results in more repeatable weld quality than position control welding mode [23]. In the present study, this mode is used to compensate the axial tool deviation along the normal sample axis due to the robot

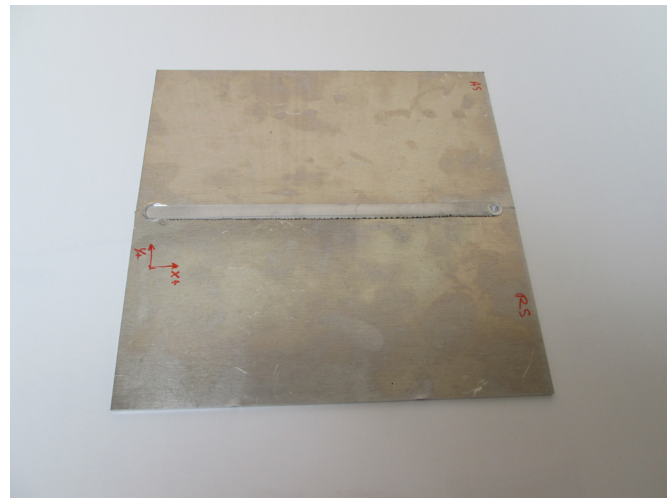

Fig. 2. 3-mm thick AA 5754-H22 FSWed coupons.

Fig. 3. Gantry type Vernier CNC machine.

Fig. 4. RFSW test-bed incorporating a FANUC S900iB/400 RJ3iB industrial robot and an electrically driven process end-effector.