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FSW process tolerance according to the position and orientation of the tool: requirement for the means of production design

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Abstract: Friction Stir Welding (FSW) is an innovative welding process increasingly used by industry for the welding of aluminum alloys. In order to reduce the high investment costs of a dedicated FSW's machine and in order to offer more flexibility to weld complex geometry, high payload robots may be used. A serial kinematics robot meets these specifications but under the stresses generated during welding, its structure readily deforms. The consequences are deviations of the tool nominal position with respect to the seam. The work presented here proposes to study the process tolerances with tool positioning defect. An experimental study enables to evaluate the influence of the tool position disorientation on weld quality, the travel force and torque generated. The objective is to estimate the impact of the disorientation on the tool mechanical interactions when welding using a serial kinematics robot.

Introduction - Friction Stir Welding

To perform FSW, a rotating FSW tool, composed by a shoulder and a pin is inserted in the work pieces to be welded rigidly clamped. Thanks a down force (F_z), applied along the rotational axis, the tool plunges into the work pieces until the shoulder reaches the upper surface (Fig. 1). After a dwell time, the tool is given a velocity, along the seam, to create the weld bead. The processing parameters (rotational speed, travel speed and down force F_z) are chosen such that the mechanical heat energy provided, to the material to generate a weld without internal defect, is sufficient. In consequences, during the FSW process mechanical interactions (i.e. forces in the three directions and torque) are applied by the material on the tool (Fig. 1) [3, 6]. The applied forces and torque are impacting the choice of the FSW machine (robot, milling machine or dedicated machine) and the whole clamping device. A FSW machine has to apply the processing parameter required to obtain a sound weld and maintain a constant tool position, according to the work piece surface, along the welding path. The research work presented here proposes to study the tolerances of FSW process according to tool orientation. The defect establishment and the impact of the forces will be studied. This kind of defect can occur as welding with a serial kinematics robot.

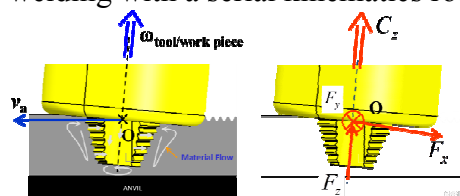


Fig. 1: Diagram of FSW local principle

Presentation of the problematic

FSW is a solid state welding process [1]. Its first characteristic permits it to weld the aluminum with poor solidification microstructure and porosity in the welded zone [2]. The second one, as fusion welding, it has the ability to weld complex geometry. In order to fully use this advantage, it is

necessary to perform the weld with machine with 5 or 6 degree of freedom and a large workspace. The high payloads serial kinematics robot fulfills these characteristics. However, this machine faces two major problematic:

- In FSW, the tool axial position is controlled in force, not in position,
- The forces generated during welding generate elastic deformation of the robot structure. The deformation involves tool position and orientation defects according to the nominal position given by the surface.

The elastic deformation of the robot structure will generate two kind of tool position defect:

- A tool deviation from the seam [7]. It leads to a weld not positioned on the middle on the seam,
- A wrong orientation of the tool according to the nominal position.

Depending of the amplitude of these defects, they can generate defect inside the weld bead. Moreover, the range of the forces and torque applied on the tool are depending on the tool orientation. The resulting orientation of the tool comes from two combined causes: the force applied during welding and the robot deformation. The studied configuration is the welding of a linear but joint. In this configuration, we can associate for each location of the welded seam, a local orthonormal reference frame $R_p(O, x_p, y_p, z_p)$. The welded seam is defined as the line generated by the joining of two surfaces without any gap. x_p is the vector tangent to the seam (the welding path) oriented in the direction of the welding speed. z_p is the vector normal to work piece's surface to be welded. In the R_p frame, the tool orientation can be defined thanks two angle ψ and ϕ . They are presented on Fig. 2 a. In order to define the tool position, it is necessary to define the tool center, point O, and the associate reference frame. A FSW tool is composed by a pin and a shoulder. In most of the case, it is possible to define the geometrical surface envelope of the pin and the shoulder. The geometrical surface envelope of the pin is a cylinder or a cone. The shoulder can be characterized by a plane, a cone or a spherical cap. If the geometry is considered as perfect, the revolution axis of the pin and shoulder surface envelope are identical. The tool center can be defined as the intersection of the tool surface envelope rotational axis and the tangent plane formed at the intersection between the shoulder and pin surfaces envelopes (see Fig. 2 b). During FSW process, it is supposed that the tool revolution and rotation axis are the same.

In the tool referential frame work, it can be written during welding:

- The tool kinematics:

$$\vec{\Omega}_{(tool/workpiece)} = \omega \cdot \vec{z}_{tool} \quad - \quad \vec{V}_{(tool/workpiece, O)} = V_a \cdot \vec{x}_p + \delta_z \cdot \vec{z}_{tool} \quad (1) \text{ and } (2)$$

- The forces (3) and momentum (4) applied on the tool by the work piece material on point O:

$$\vec{F}_{tool/workpiece} = F_x \cdot \vec{x}_{tool} + F_y \cdot \vec{y}_{tool} + F_z \cdot \vec{z}_{tool} \quad \vec{T}_{tool/workpiece, O} = L_x \times \vec{x}_{tool} + L_y \times \vec{y}_{tool} + C_z \times \vec{z}_{tool} \quad (3) \text{ and } (4)$$

The element δ_z correspond to the tool position variation along the rotational axis during welding as the tool position is force controlled. It corresponds to a variation of the depth. Therefore, during welding the tool position can fluctuate because its position is depending on the equilibrium between the force applied by the machine on the tool and those applied by the work piece material on the tool. Thus, the tool position and orientation can be defined by the relation (5) and (6):

$$\vec{O_p O_{outil}} = \delta_y \vec{y}_p + \delta_z \vec{z}_{outil} \quad \vec{z}_{outil} = \cos \phi \cos \psi \vec{z}_p - \cos \phi \sin \psi \vec{y}_p + \sin \phi \vec{x}_p \quad (5) \text{ and } (6)$$

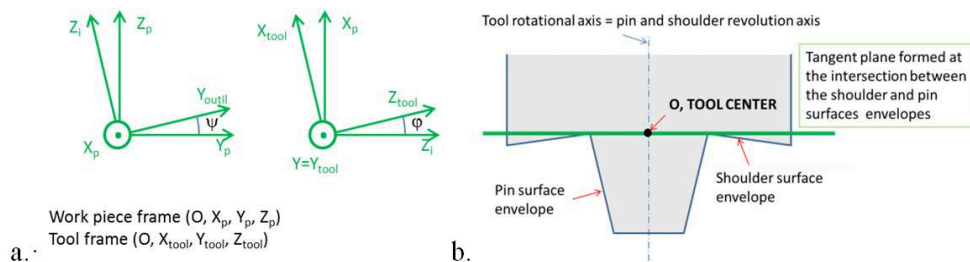


Fig. 2: Presentation of the local frame (R_p) and the tool frame (R_{tool})

In stationary welding conditions, the plunge depth can be considered as being stable, thus the velocity element on the tool centre, δ_z , is equal to zero. Also, as welding a linear butt weld, the tool is generally centred on the seam (i.e. $\delta_y=0$) and no lateral side tilt angle is given ($\psi=0$). The defects studied in this work are the one that could be generated as welding with a serial kinematics robot due to its elastic deformation. These are:

- Variation of the tool rotation angle (ψ and ϕ according to the surface. Where ψ is the side tilt angle and ϕ is the tilt angle [8].
- Variation of tool position according to the seam δ_y , i.e. the tool knows a lateral offset [8].
The tool is then not anymore centred on the seam.

For the studied configuration, the objective of this work presented is:

- to define the position and orientation process tolerance interval according to the seam,
- to identify the kind of defect restricting the process tolerance interval,
- to analyze the evolution of the forces and torque according to the tool position and orientation.

This last point, as welding with a flexible machine like a serial kinematics robot must permit to understand the link between the robot deformation and the tool / work piece mechanical interactions. In the next paragraph, the study case and the experimental procedure are described. The processing parameters (axial force, travel speed, rotational speed and tilt angle) of a reference trial are determined. This reference trial leads to a sound weld. The forces and torque measured during welding are given. The defects visualized are presented in the tables according to the processing parameter. The descriptions of the experimental results are presented on the third paragraph. The analysis of the forces and torque evolution according the position and orientation variations are presented in this paragraph.

Description of the experimental procedure

The study case is the following: linear butt welding of two plates 6mm thick EN AW 6082-T651. The length welded is about 300mm. The tool shoulder diameter is 21mm and the pin length is slightly lower than 6mm. The pin is threaded and has a cylindrical surface envelope. The shoulder has a concave surface envelope (Fig. 2). The welding operation is force controlled, as it is advised as welding with a serial kinematics robot [4]. The goals of these trials are to study the defect generated and the evolution of the forces and torque even if the studied configuration is not weld able with a robot (axial force F_z must be below 10kN). The experiments are done on the FSW dedicated machine MTS I-Stir 10 from the Institut de Soudure. It is a machine that can be considered as being rigid and it allows the welding operation in force control. Moreover, this hydraulic machine measures the forces applied on the tool in the three directions and the resistive rotational torque during the whole welding process. In a first time, a reference weld has been identified, weld presenting any internal defect. The welded conditions are given in the Table 1. It is to be noted that, the analysis of the forces and torque studies will be based on the mean value recorded as welding in stationary condition (i.e. constant processing parameters). For each trial, the force and torque amplitude have been controlled in order to see any mismatch. ϕ corresponds to angle opposite to the travel direction, it is generally called “tilt angle” [8].

Table 1: Processing parameters of the reference weld

Travel Speed	Rotational Speed	Axial Force	ϕ	ψ	Position according to the
mm/min	tr/min	kN	°	°	mm
600	1300	16	2,5	0	0

A parametrical study has been done on the three parameters identified previously: the two angles determining the orientation of the tool rotational axis (ϕ , ψ) and the tool position according to the seam (δ_y). In the experimental study, each parameter has been studied separately with the other parameters given as in Table 1. So, the combined effect is not studied here. The Table 2 presents the values tested for the three parameters. Due to the tool kinematics, the temperature and strain fields are not symmetrical according to the seam. Therefore, it is not possible to reduce the trials number by considering the symmetry. The δ_y negative values correspond to the shifting of the tool in the

advancing side direction (i.e. positive values means to the advancing side). Similarly, the negative values of angle ψ correspond to a tool side tilt in the advancing side. The Fig. 3 illustrates the tool position performed during the experiment.

Table 2: Processing parameters used during the experimental study

Rotational Speed	Travel Speed	Axial Force	ϕ		ψ		δ_y	
			Value Interval	Step	Value Interval	Step	Value Interval	Step
1300 tr/min	600 mm/min	16 kN	0.5°; 5.5°	1°	(-8°) ; 8°	2°	(-6) ; 6	1

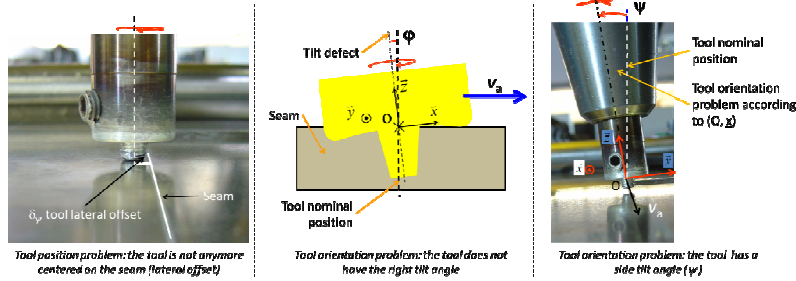


Fig. 3: Presentation of the studied defect, experimental implementation

Results and discussions

The Table 3 presents the welds soundness (realized per macro-graphical inspection) for each tested weld configuration. When the tool has a lateral offset (Table 3 – A) greater than 2mm, the weld present an incomplete penetration. There is no difference visualized between an offset according to advancing or retreating side. The asymmetry of the weld is too small to generate a difference. For the tilt angle ϕ (Table 3 – B), as it is too much “tilted” ($\phi > 3.5^\circ$) an incomplete penetration is also noticed. Due to the tilt angle, the pin bottom is not anymore close enough from the bottom surface. On the other side, as the tilt angle ϕ is near to be equal to zero, i.e. the rotational axis is almost perpendicular to the surface, the tool plunge increases leading to an excessive penetration. This is a consequence of the concave surface envelope of the shoulder. Indeed, a concave shoulder cannot be used with a 0° tilt angle only flat shoulder can weld with this angle. As welding with a side tilt angle ψ , even if the angle is given against advancing side or retreating side, it leads to work piece thickness thinning also leading to an excessive flash. In this condition, the tool heel is not anymore acting only on the back of the weld, but also on the side. So, the heel knows a plunge depth also laterally leading to excessive toe flash. In this case, material has been expelled, forming the excessing flash, due to the heel lateral plunges inside the work piece. Depending of acceptance criteria, this defect can be tolerated if the angle does not exceed 2° . Below 2° , no significant thinning has been noticed. These results are depending on the processing parameter and the tool geometry.

Table 3: Defect obtained for the different tool position and orientation tested

A - Tool position problem: the tool is not anymore centered on the seam (lateral offset)

δ_y (mm)	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6
Defect	IP	IP	IP	IP	OK	OK	OK	OK	OK	IP	IP	IP	IP

IP: Incomplete Penetration OK: Sound weld

B - Tool orientation problem: the tool does not have the right tilt angle

ϕ (°)	0.5	1.5	2.5	3.5	4.5
Defect	EP	OK	OK	OK	IP

EP: Excessive Penetration, IP: Incomplete Penetration

C - Tool orientation problem: the tool has a side tilt angle (ψ)

ψ (°)	-8	-6	-4	-2	0	2	4	6	8
DéfaTt	T	T	T	OK	OK	OK	T	T	T

T: Work piece thickness thinning, OK: Sound weld

In FSW, the width of the stirred zone is not uniform over the entire thickness. At the upper surface, the width corresponds to the shoulder diameter. At the bottom surface, if the tool penetration is sufficient, the stirred zone width is approximately equal to the pin extremity diameter [3]. If the tool lateral offset is about equal to the pin extremity radius, the weld will present an incomplete penetration. When, the lateral offset still increase, the height presenting no stirring will be greater [3]. Therefore, the tolerance of this defect will strongly depend on the stir zone itself depending on the tool geometry on the processing parameters. Regarding the forces, in the three directions and the

torque, as the tool is given a lateral offset, no relevant amplitudes modifications have been observed. Therefore, the location of the work piece interface doesn't influence the forces and torque applied on the tool and consequently the stirring. During welding, the stirred material is confined between the shoulder, the anvil and the work piece [2]. The flash appeared when the shoulder cannot keep anymore the plasticized material confined under the shoulder. This can be due to hot welding conditions or like in our study case due to a side tilt angle, ψ too important. This excessive flash can generally be associated to work piece thickness thinning. The incomplete penetration occurs due to a bad tool position or also as the tool has the wrong orientation. With a wrong orientation the distance between the end of the pin and the anvil is modified and also the location of the stirred zone. Then, at the bottom of the work piece, insufficient stirring will generate the incomplete penetration defect. This case is corresponding to a great tilt angle, ϕ . The work piece thickness thinning is observed for high values of side tilt angle, ψ , corresponding to the lateral penetration of the shoulder inside the work piece. The Fig. 4 presents the mean value of the torque evolution according to the tilts variations, ϕ and ψ .

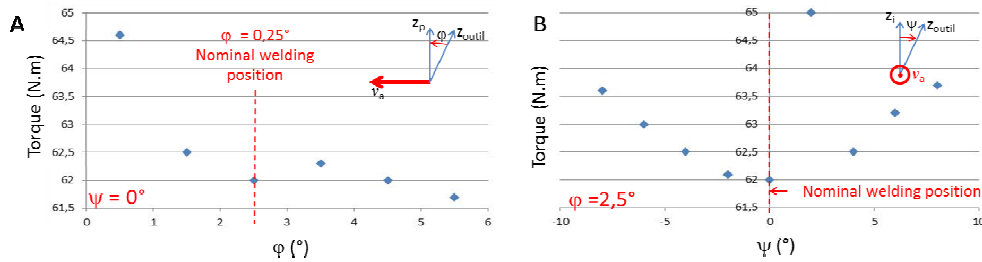


Fig. 4: Torque evolution according to tilt angle, ϕ (A) and side tilt angle, ψ (B)

The torque is the resistance acting on the tool generated by the material to be stirred. According to Fig. 4, the torque value is influenced by the tilts evolutions. As the tilt angle, ϕ , is modified from 2.5° to 0.5° (Fig. 4-A), the torque is increasing. From 2.5° to 5.5° the evaluation is not so clear and the torque seems to remain constant. Generally, as welding with a serial kinematics robots, the operator has a tendency to give more tilt in order to weld complex geometry. So, this practice has no influence on the torque generated. Regarding the torque evolution as a side tilt angle, ψ , is given to the tool (Fig. 4-B) a torque minimum value was measured for $\psi = 0$ and an aberrant point was observed for an angle equal to 2.5° . The torque is one of the two preponderant factors determining the weld power. Indeed, the power related to the travel speed is negligible with regards of the total power. As for each trial the travel and the rotational speeds are identical, the nominal energy and thus the temperature is proportional to the torque. The excess of tool penetration observed for small values of side tilt angle ψ is probably due to higher welding temperature conditions generated by the torque increase. It is difficult to establish a relation between the torque increase and the evolution of the side tilt angle. However, it seems to be possible to establish a relationship between the torque and the penetration increase. A torque increase involves an increase of welding energy. This one conduces to a temperature increase and thus decreases the yield stress explaining the tool penetration increase and the related flash even for small values of side tilt angle. Concerning the travel force evolution, it is important to note that it is not the force acting in the direction of the travel speed. This force is acting along the direction of a vector perpendicular to the rotational axis tilted from the angle ϕ . This vector is called x_{outil} and is illustrated on Fig. 2.a. So, in this paper the travel force considered is the force along the vector x_{outil} . By giving a greater tilt angle, a greater part of the axial force F_z is oriented in the travel direction helping the tool to be moved along the seam. The Fig. 5 presents the evolution of the travel force according to the tool orientation. First of all, it is important to note that the side tilt angle, ψ , do not contribute to transmit a part of the axial force to the travel force. The travel force increases with an increase of tilt angle ϕ principally due to the contribution of the axial force F_z in the travel force and the shoulder penetration on the back of the tool. The evolution of the travel force according to the side tilt angle, ψ , is not symmetrical as it was the case for the torque. For negative value of ψ (tool tilted to the advancing side), the travel force is increasing with the angle increase. For positive value of ψ (tool tilted to the retreating side),

the force evolution is not significant. Under the shoulder, the relative velocity tool / work piece are opposite sign regarding advancing or retreating side. The travel force intensity comes from the friction difference between the advancing side (which resist to the tool travel motion) and the retreating side (which acts in direction of the travel direction). By tilting the tool towards the advancing side, the friction increases on this side of the tool generating a travel force increase. By tilting the tool towards the retreating side, the friction increases on this side of the tool but this increase could be limited by the material heating as the retreating side is the weld coldest side [5].

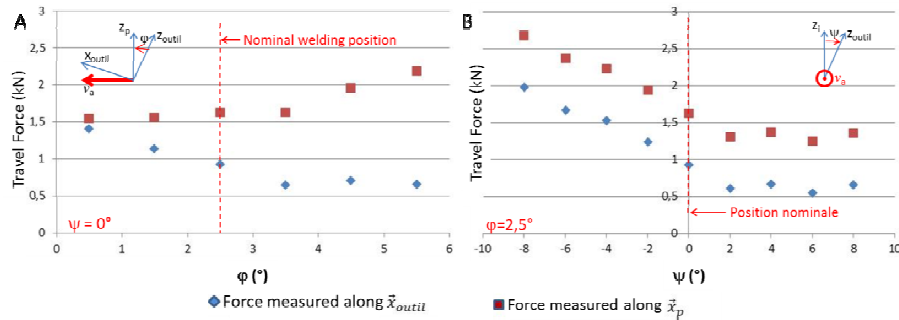


Fig. 5: Travel force according to tilt angle, ϕ (A) and side tilt angle, ψ (B)

Conclusion and perspectives

The use of serial kinematics robot to perform FSW applications require to take interest at the forces and torques evolutions in order to determine the tolerances of FSW process according to tool positions and orientation. Welding forces are generating an elastic deformation of the robot structure, which will lead to defect on tool trajectory (position and orientation). A wrong tool orientation may contribute to increase the welding forces amplitude. Thus, the robotization problematic is related. In order to solve partially this problematic, it was proposed to use the experimental procedure to identify the process window in order to characterize the defect generated as welding with a serial kinematics robot.

In future work, it will also be necessary to take into account the defect generated by the work piece manufacturing process. For example, it will study the weld quality obtain and the forces generated if the seam present a gap between the two work piece or they present two different thickness.

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