Using the plunging and welding process windows to determine a FSW means of production

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Abstract: This paper presents an experimental methodology to determine a Friction Stir Welding (FSW) means of production based on the experimental study of the tool / material mechanical interactions generated during the plunging and welding stages. These two stages have been identified as being characteristic for the qualification of a FSW equipment. This paper presents the experimental results of the parametric study done on the plunging and welding phases. Ranges of forces and torques diagrams were established according to the processing parameters, in order to qualify a means of production and select the process parameters allowing the operation on the available FSW equipment.

Introduction

Friction Stir Welding (FSW) is an innovative welding process commonly known as being a solid state welding process [1]. Its particularity is to join material without reaching the fusion temperature, giving it the availability to weld almost all types of aluminum alloys, even the one classified as non-weldable by fusion welding due to hot cracking and poor solidification microstructure in the fusion zone, like the 2000 or the 7000 aluminum alloy [2]. To perform FSW, a non-consumable rotating tool, composed by a shoulder and a pin, is inserted into the interface of two rigidly clamped workpieces to avoid any movement. Once the shoulder in contact with the workpieces surface, it is moved along the joint line, bounding the workpieces together by heating and stirring the workpieces material. The welding processing parameters, axial force F_z, travel speed v_a and spindle rotational frequency N, are ensuring the required heat energy input to create the join. The process generates non-negligible process forces and torques which are transmitted to the welding equipment, impacting its characteristics.

Today, most applications are in the transportation industries. With its characteristics, Friction Stir Welding should be more widespread in the industry. The lacks of industry standards, design guidelines and informed axial force or the *high cost of capital equipment* are, according to Arbegast [3], barriers to the FSW expansion. Our research work is the industrialisation of the FSW, in order to provide tools to industrials to qualify a welding equipment and define its technical requirements. Therefore, a methodology based on the analysis of the kinematical and mechanical interactions generated during welding between the product, the process and the resources was developed by Zimmer and al. [4]. The idea is to analyze the interactions generated during welding between the tool / workpiece and the tool / material. The analysis of the tool / workpiece interactions, a global approach, leads to the determination of the position and orientation of the tool during welding, according to the welding surface and to the definition of the tool trajectory. So, it defines the *equipment workspace required* and the tool accessibility. In the other way, the study of tool / material interactions is a more local approach. It describes the tool position and orientation, according to the welding surface. It also defines the *tool kinematics* and the *mechanical load applied on the tool*. It leads to the determination of the characteristics parameters in order to write down the technical requirements for the equipment. This paper will concentrate on *the experimental analysis of the tool / material mechanical interactions* occurring during FSW and of the influence of the processing parameters on them.

Global analysis of the mechanical interaction generated during FSW

The tool / material mechanical interactions have been analyzed through the process forces and torque generated. To proceed, the welding process has been decomposed into 6 independent phases. The Fig. 1 presents the phase's decompositions and the mechanical interaction applied on the tool during FSW. The study, performed on several aluminium alloy and thicknesses, shows that the plunge and welding at constant speed stage are characteristic for a static qualification of the welding equipment [4]. During the plunge stage, the axial force F_z and spindle torque C_z know a maximum at the end of plunge. These short peaks were identified as being characteristic for a static qualification of the welding equipment [4]. In the same manner the spindle torque, the axial forces, F_z, and the forces F_x and F_y which can be greater than 10% of F_z according to the processing parameters, are characteristic for a static qualification of the welding equipment [4]. Therefore, in order to enable the use of standard equipment allowing the FSW of complex geometries a parametric study has been realized on these two characteristic phases to see if the load transmitted to the welding equipment can be reduced. All the trials were performed on an instrumented MTS-ISTIR-10 Friction Stir Welder at the Institut de Soudure on a 6mm thick, 6000 aluminium alloy series. For all trials, the plunging stage was displacement controlled and the welding stage was force controlled.

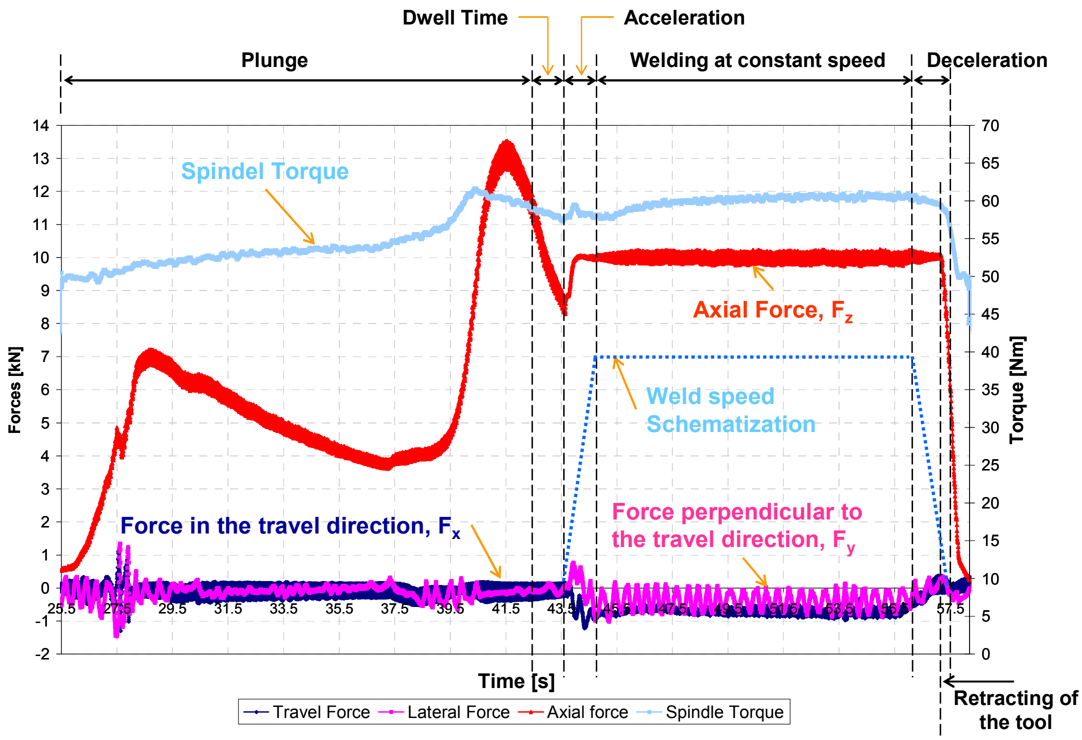

Fig. 1: Forces and spindle torque applied on the tool during the friction stir operation of 6000 aluminum alloy

Plunge and welding stages experimental investigation

The Fig. 2 presents the input and output parameters of the two studied stages with an emphasis on the load transmitted to the FSW welding equipment. Special attention will be paid to the influence of the FSW processing parameters on these parameters. Firstly, the main results will be presented for the plunging stage, then for the welding at constant speed stage.

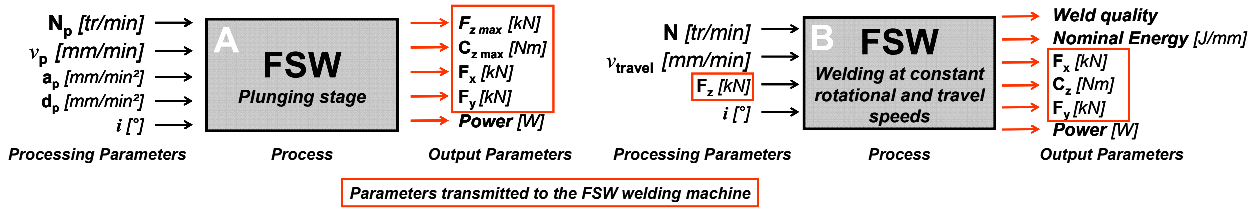

Fig. 2: Relationship between the studied output and input parameters, A for the plunge stage, B for the welding at constant speed stage.

Analysis of the plunge stage

Experimental procedure

Plunge experimental testing were performed in order to study the influence of the principal processing parameters, Fig. 2, the rotational speed N_p and the plunging speed v_p,, on the maximal axial force and torque, $F_{z\,max}$ and $C_{z\,max}$. To proceed a variation of 33% and a 66% was applied on N_p and v_p according to the plunge processing parameters used during the welding operation. The tool acceleration / deceleration were calibrated in the same manner for each trial.

Evolution of the output parameters when N_p and v_p are evolving

The Fig. 3 presents the evolution of $F_{z\,max}$ and $C_{z\,max}$ according to N_p for v_p set up at different values, respectively 7, 14, 20, 27 and 35 mm/min. Two general tendencies can be identified. The first one is for a given N_p, the values of $F_{z\,max}$ and $C_{z\,max}$ increases as v_p increases. The second tendency is for a given v_p, as N_p increases, the maximal forces and torques decreases. This is due to the change of the generated thermo-mechanical interactions between the tool and the workpiece. The global analysis shows that $F_{z\,max}$ is a function of N_p and v_p but is more sensitive to the evolutions of v_p than N_p. On the other side, $C_{z\,max}$ is still a function N_p and v_p but is more sensitive to the evolutions of N_p than v_p. So, the lowest axial force and spindle torque occurred when the spindle frequency is the highest and the plunging speed is the lowest, i.e. when the heat input generated due to friction between the tool and the workpiece is the highest and the generated heat has time to be dissipated inside the workpiece by conduction, increasing the workpiece temperature in the plunging zone.

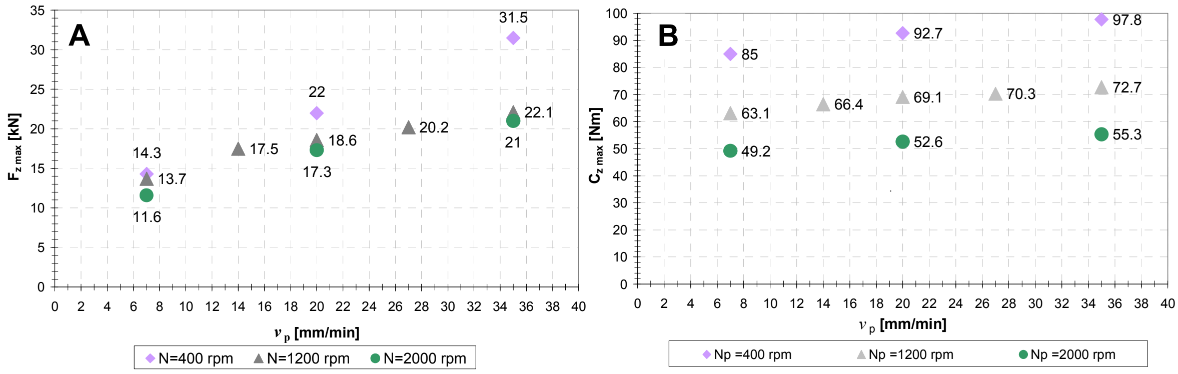

Fig. 3: A - $F_{z\,max}$ evolution according to N_p for v_p set up as constant. B- $C_{z\,max}$ evolution according to N_p for v_p set up as constant.

Process repeatability

The Fig. 4 presents the evolution of the axial force and the spindle torque measured for three plunge trial performed at identical processing parameters. Their evolution over the plunging depth are the same, their maximal values are in the same order of magnitude and are occurring at the same location. Therefore it can be concluded that the thermo-mechanical conditions are identical and repeatable over successive trial performed at identical processing parameters. However, the experiments showed some variability of the maximal axial force value for trials performed at identical processing parameters. Peak amplitude difference can reach 20%, therefore. This variability has to be taken into account.

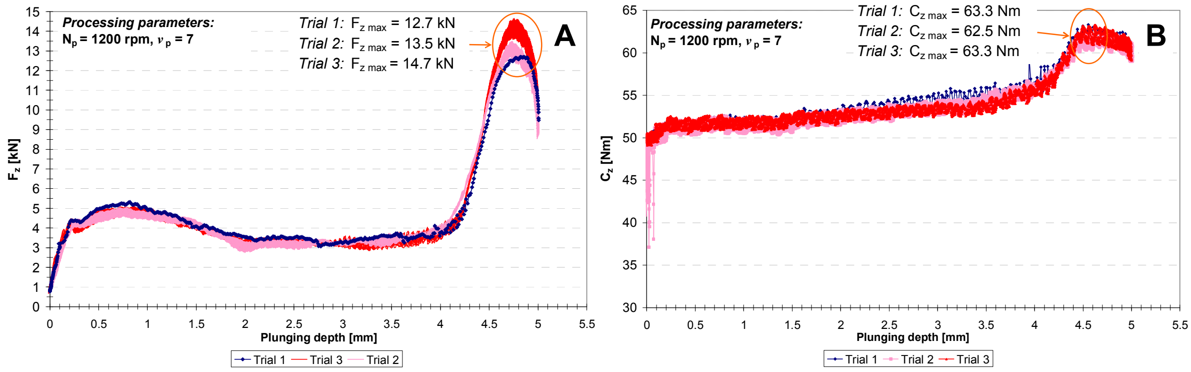

Fig. 4: Force and torque evolution of three trials done at the same processing parameters. A, axial force evolution F_z. B, spindle torque evolution C_z.

Force and torque diagram according to the processing parameters

By combining the $F_{z\ max}$ and $C_{z\ max}$ recorded inside one diagram, according to the processing parameters, one obtains what could be named a "plunging test experimental diagram", presented on Fig. 5. Forces and torques ranges can be observed. This kind of diagram is interesting for choosing the processing parameters according to the available means of production, i.e. according to the range of force and torque generated. It can also be used to select the best compromise between the developed forces and torque and the stage productivity related to the plunge velocity.

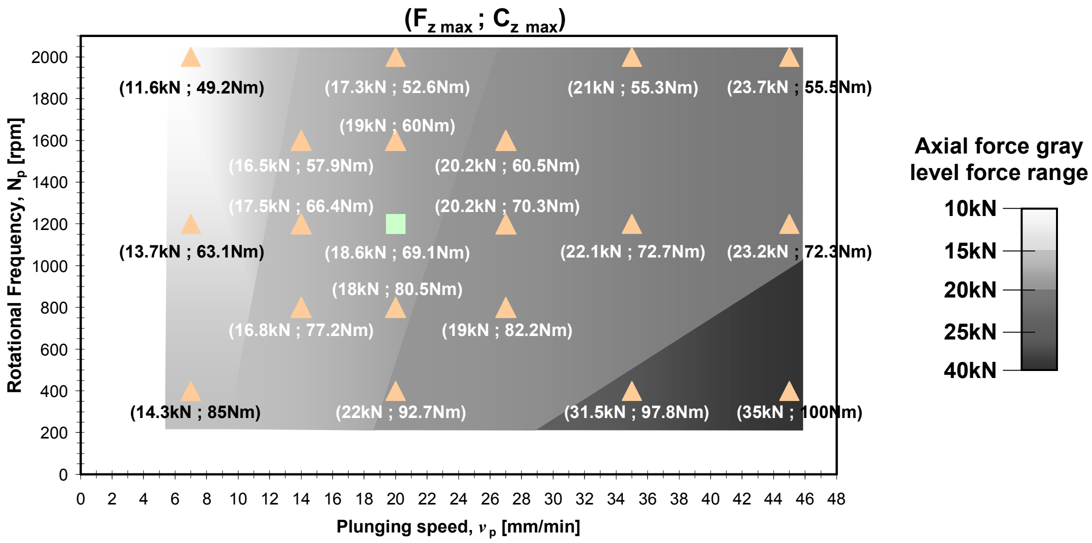

Fig. 5: Maximal axial force and spindle torque according to Np and v_p

To qualify a FSW welding equipment, it is important to consider the plunging but also the welding at constant speed stage. Therefore, an experimental study has also been made on this stage. It would be interesting, from an industrialization point of view, to draw a diagram equivalent of the Fig. 5 for the welding stage.

Analysis of the welding at constant speed stage

The analysis of the welding at constant stage was performed through the determination of the studied alloy process windows. The criterion for its definition was the realization of a sound weld, i.e. without any internal or external defect. The varying parameters are the three principal welding processing parameters, the tool rotational speed, N, the travel speed, v_a and the axial force F_z. The tilt angle remained fixed at the tool geometry optimal value.

Experimental procedure

On the welding stage, the most characteristic parameter for a static qualification of a welding equipment is a process input parameter, F_z, Fig. 2. So, this parameter is controlled but its setting is related to material thermo-mechanical conditions leading from the tool / workpiece mechanical interactions resulting from the application of N, v_a and F_z. So, the applied force is depending on the material and thickness to be welded, the tool geometry, N and v_a. The determination of the process window of the studied material showed that it was possible to applied different ranges of forces for a given N and v_a.

Evolution of the travel force, F_x, and Cz when N and F_z is evolving

On the Fig. 6-– A, the spindle torque mean value evolution can be observed, for a given v_a, according to F_z and N. The spindle torque is reduced when the spindle frequency is increased. Higher spindle frequency implies higher material strain rate around the tool but also a frictional heat input increase leading to a material temperature increase. The temperature increase and the high material strain rate, due to the stirring, are reducing the material consistency and consequently its viscosity involving the rotational drag reduction. The analysis showed that the spindle torque doesn't seem to be sensitive to the travel speed increase and it can be concluded that the material flow around the tool, related to the tool travel motion, isn't significant in the material heat input. However, the travel force F_x is very sensitive to variation of v_a, Fig. 6-B. F_x is decreasing with a decrease of v_a and consequently an heat input decrease, at N constant. This travel force decrease could be explained by an increase of the plasticised zone in front of the pin, due to more heat input, facilitating the tool travel along the workpiece interface [5]. The results showed that F_x maximal values could reach 38% of the parameterized value F_z. Therefore, F_x has to be taken into account for a static qualification of a FSW equipment.

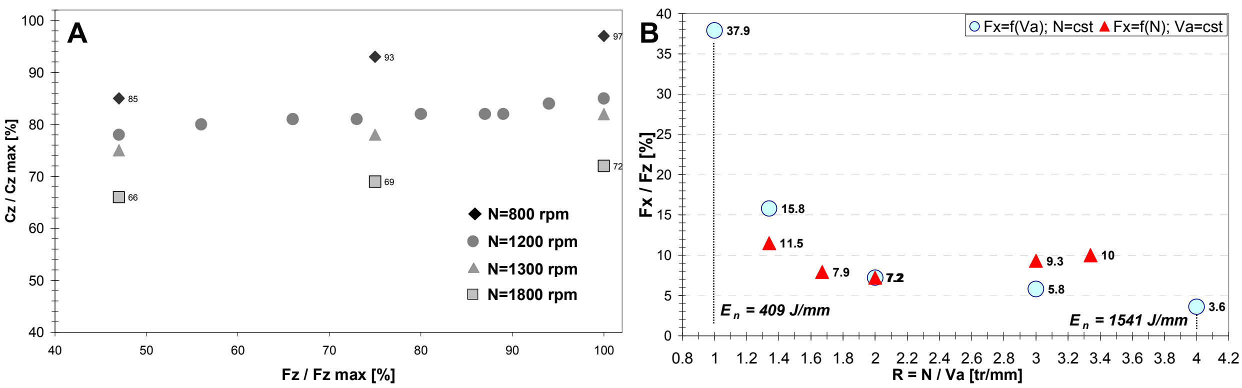

Fig. 6: A- Presentation of the spindle torque evolution according to N and F_z. B- Travel force, F_x, evolution according to R for N and v_a constant.

The forces and toque analysis showed that the C_z, F_x and F_y can be influenced by the processing parameters. It also showed that for a given N and v_a, for our material, thickness and tool a range of different process force can be applied.

Force range diagram according to the processing parameters

By plotting the process force according to N and v_a leading to a sound weld into a diagram, ranges of forces can be distinguished, Fig. 7. The same diagram can be drawn for the spindle torque. This representation permit to select the welding processing parameter combination (F_z, N, v_a) according to the available FSW equipment or to the required process productivity. More generally, the study showed that it was possible to reduce the process forces by working on the processing parameters in order to allow the welding with a standard and flexible mean of production, like a robot *to reduce the investment cost*.

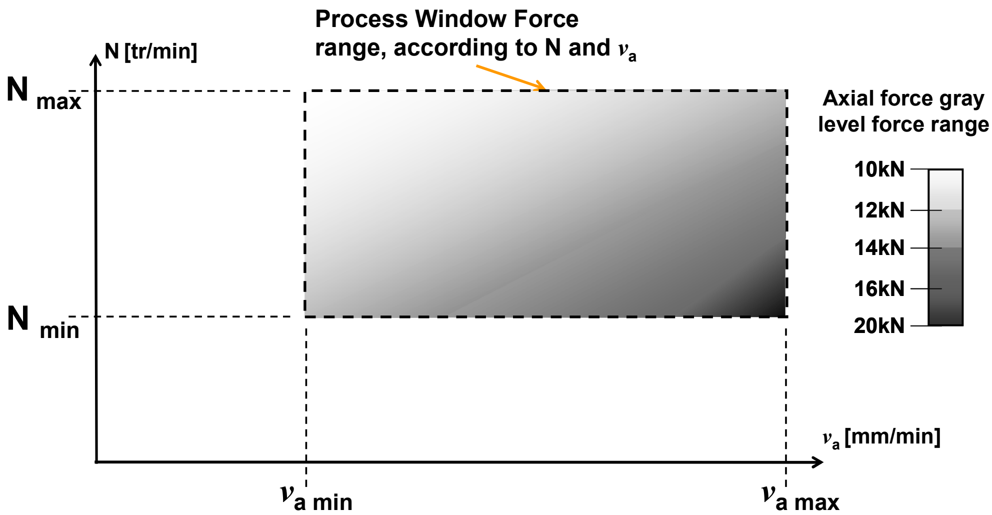

Fig. 7: Welding process windows and force ranges

The established diagrams, Fig. 5 and Fig. 7, are interesting tools for the process industrialization, because they entirely define the FSW operation. Furthermore, they permit to select the processing parameters according to the generated forces and torque according to available welding equipment characteristics. They should be defined for different material, thicknesses and tool geometries in order to form a process parameters welding data base like it is available in machining. The establishment of these kind diagrams is probably the key to the FSW expansion but one step should be done before, the standardization of the tool geometries.

Conclusion and future work

To qualify a FSW equipment experimental investigations have been performed on the welding at constant speed stage and the plunging stage. It permits to evaluate the tool / material interactions through the process forces and torque generation according to the processing parameters, for one material, thickness and tool geometry. The experimental results permit to establish diagrams presenting the axial force according to the processing for the two stages characteristics for a FSW equipment static qualification. These diagrams permit to select the process windows ranges allowing the FSW with the available mean of production. To complete these work, another dimension should be added to this diagram, the weld mechanical properties in order to select the processing according to the weld quality and the available FSW equipment.

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