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Additive Friction Stir Manufacturing Process: Interest in Understanding Thermal Phenomena and Numerical Modeling of the Temperature Rise Phase

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***Abstract*—**Additive Friction Stir Manufacturing, or AFSM, is a new industrial process that follows the emergence of friction-based processes. The AFSM process is a solid-state additive process using the energy produced by the friction at the interface between a rotating non-consumable tool and a substrate. Friction depends on various parameters like axial force, rotation speed or friction coefficient. The feeder material is a metallic rod that flows through a hole in the tool. There is still a lack in understanding of the physical phenomena taking place during the process. This research aims at a better AFSM process understanding and implementation, thanks to numerical simulation and experimental validation performed on a prototype effector. Such an approach is considered a promising way for studying the influence of the process parameters and to finally identify a process window that seems relevant. The deposition of material through the AFSM process takes place in several phases. In chronological order these phases are the docking phase, the dwell time phase, the deposition phase, and the removal phase. The present work focuses on the dwell time phase that enables the temperature rise of the system due to pure friction. An analytic modeling of heat generation based on friction considers as main parameters the rotational speed and the contact pressure. Another parameter considered influential is the friction coefficient assumed to be variable, due to the self-lubrication of the system with the rise in temperature or the materials in contact roughness smoothing over time. This study proposes through a numerical modeling followed by an experimental validation to question the influence of the various input parameters on the dwell time phase. Rotation speed, temperature, spindle torque and axial force are the main monitored parameters during experimentations and serve as reference data for the calibration of the numerical model. This research shows that the geometry of the tool as well as fluctuations of the input parameters like axial force and rotational speed are very influential on the temperature reached and/or the time required to reach the targeted temperature. The main outcome is the prediction of a process window which is a key result for a more efficient process implementation.

***Keywords*—**Numerical Model, additive manufacturing, frictional heat generation.

I. Introduction

THIS research is committed to supporting the development of an innovative process with a strong interest from the industrial world. Most current metal additive manufacturing technologies are based on metal melting. These processes may encounter certain limitations due to the temperatures involved which may cause deformations and introduce many residual stresses. The types of materials that can be used are also limited. Recently, there has been an emergence of new technologies [1], [2] exploiting the principle of the FSW [3] process and by adapting it to the needs of additive manufacturing. These new kinds of processes enable to reduce the thermal gradients and thus the residual stresses. Today, few studies on the thermal behavior during the heating phase of the process are listed [4]-[6] and are often based on coupled thermomechanical models complex to implement. However, understanding the physical phenomena during this phase appears to be essential for the rest of the process.

This research deals with an innovative additive manufacturing process involving friction as unique energy source. Development of a dedicated numerical model will aim to anticipate and determine the influence of process parameters, and so to choose the more performant experimental strategy. The identification of an optimal parametric set will lead to the optimization of the design of experiments (DOE). This study will attempt to understand and model the physical phenomena inherent to the process. In other words, it will allow to estimate the amount of energy [7] to be supplied to the system (composed of the metal, the substrate, and the tool) linked to the processing parameters to reach a temperature allowing the transition to a soft state of the material. The modification of the input parameters should enable to reach the process temperature as fast as possible. In a first approach, the development of a simple model is favored, based on the principle of pure friction under conditions of speed, axial force, and constant dynamic friction coefficient.

A comparison between the numerical model and preliminary experiment is carried out, by setting up instrumentation allowing the monitoring of temperature and axial force. The collected data serve as an input for the calibration of the numerical model. The calibrated model is then used to analyze the sensitivity of the temperature rise phase to the variations in axial force that are inevitable under real conditions.

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II. METHODOLOGY

A. System Studied

1) Experimental Setting

The equipment used for the experiments consists of a rotation effector mounted on a Kuka KR240 serial robot. This effector can rotate the friction tool up to 5000 rpm, and an axial force up to 2400 N can be applied.

The axial force is measured by using a Kistler device clamped to a welding table. The substrate is fixed to this plate with a thermal insulator in between. The temperature is measured using an Arduino assembly incorporating a K-type thermocouple housed in a hole drilled in the substrate.

The system, as shown in Fig. 1, consists of an aluminum substrate; a cylindrical steel friction tool with a geometry reducing the surface in contact with the substrate to a smaller ring; the cylindrical tool has an aluminum rod running through its center with the same characteristics as the substrate.

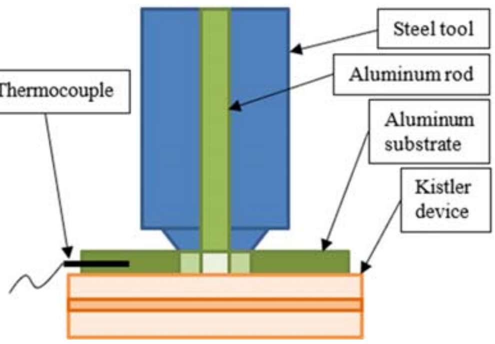

Fig. 1 System composition

2) Testing Procedure

Test takes place according to the following protocol: the rotation effector starts up to the set speed. Once the speed is reached, the robot moves the end effector along the Z-axis, thus reducing the distance between the friction tool and the substrate until the contact is made. Then, the robot progressively applies the axial force until the defined axial force is reached, which is controlled in real time thanks to the measuring device. The test ends in three cases: the predefined duration of the test is reached; the maximum target temperature is reached; the technical device does not allow the test to continue.

B. Numerical Method Description

1) Heat Generation Model, Friction Interface

The interface friction model presented by [8], [9] and based on Coulomb's law is used for the frictional heat generation model during the docking phase of the process. During this phase, pure sliding is assumed and the frictional shear stress at the interface is defined by:

$$\tau_f = \mu . p \quad (1)$$

where μ is the friction coefficient and p in MPa is the normal pressure at the interface. In this model, the heat flux generated at the contact interface is written as:

$$\dot{q} = \tau_f . v \quad (2)$$

with:

$$v = \omega . r \quad (3)$$

where τ_f is the interface frictional shear stress in MPa defined in (1) and v is the friction velocity in *mm.s*$^{-1}$ at the interface, ω is the angular velocity in *rad.s*$^{-1}$ and r the radial distance in *mm*.

2) Geometrical Model and Implementation of the Numerical Simulation

A thermal model is implemented to simulate the heat flow calculation during the temperature rise phase (or dwelling phase) using finite element method.

The mesh of the geometry Fig. 2 representing the system is defined on the GMSH software, it is composed of tetrahedral elements. The overall system is made up of three groups, associated with the substrate, with the tool and with the bar. The elements are refined at the contacting surfaces. The solver used for the numerical simulation is MORFEO (Manufacturing ORiented Finite Element tOol) developed by GEONX.

3) Materials' Properties

Materials are aluminum for the substrate and the rod and steel for the tool. The properties considered in the model are presented in Table I.

TABLE I
PROPERTIES OF MATERIALS USED

Material	Thermal Conductivity	Thermal Mass Capacity	Density
	($W.m^{-1}.K^{-1}$)	($J.kg^{-1}.K^{-1}$)	($kg.m^{-3}$)
Aluminum	230	900	2700
Steel	130	500	7800

4) Boundary Conditions and Initial Conditions

The boundary conditions applied to the system are a convective flux on the side faces with a coefficient of $20\,\mathrm{W.m^{-2}.K^{-1}}$ simulating the contact between air and the outer surfaces of the system, and another convective flux is applied on the bottom surface of the substrate with a coefficient of $1\,\mathrm{W.m^{-2}.K^{-1}}$ simulating the contact between insulation and the bottom surface of the substrate. Initial temperature is set to 20 °C.

III. RESULTS

A. Estimation of a First Set of Operating Parameters by Numerical Simulation

The process involves bringing two metal parts into contact under conditions of rotation and axial force creating a frictional interface and generating a significant amount of heat. This rise in temperature of the aluminum parts leads to their softening, as the melting temperature is well below that of steel. The simulation uses the tool with a flux distributed over a ring representing the friction interface.

Fig. 3 shows the temperature distribution in section of the tool and rod after a sequence of 500 s, at 3000 rpm under an axial force of 465 N. The temperature predicted in the contact zone is 490 °C. These represents 74% of the melting temperature of the aluminum alloy, which corresponds almost to the standards for working with a malleable material for hot forging [11]. This set of parameters is therefore chosen as initial guess for experiment.

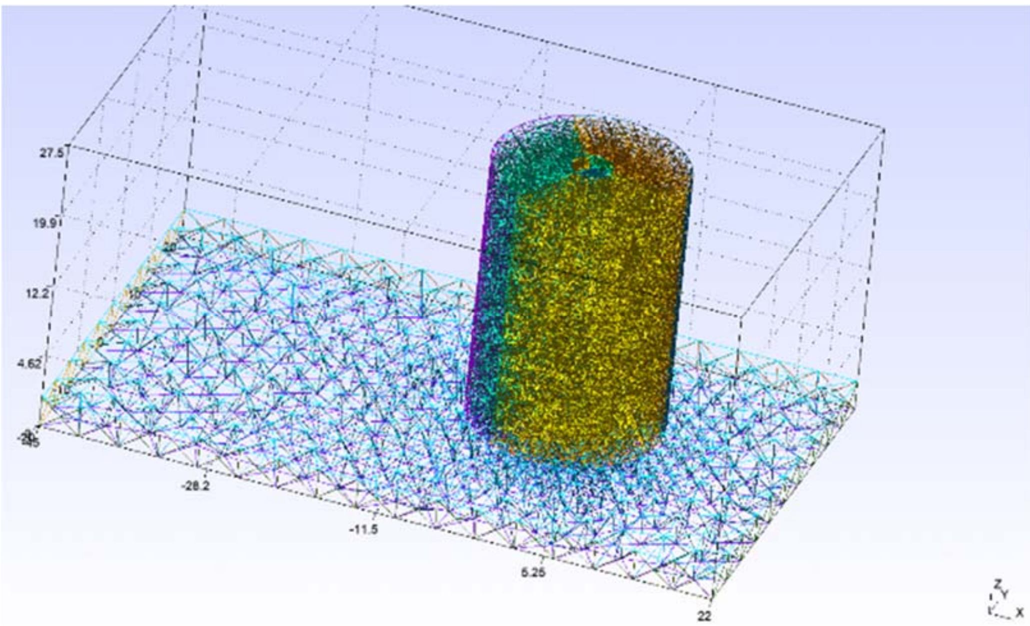

Fig. 2 Meshing of the system on GMSH

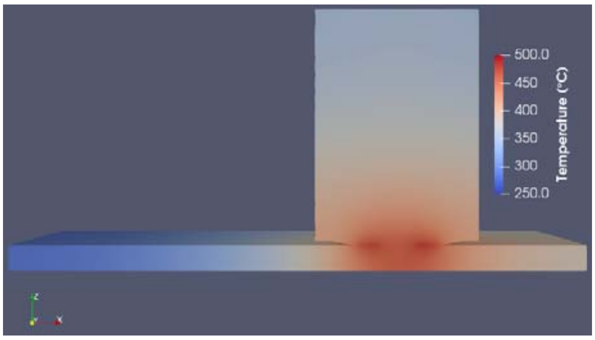

Fig. 3 Temperature distribution in the system, under 3000 rpm and 465 N during 500 s

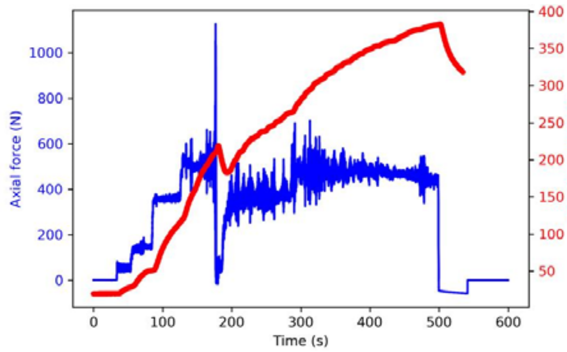

Fig. 4 Temperature, force and readings of a test

B. Results of the Experiments

The experiment consists in creating a strong contact between rotating tool and substrate to generate a friction phenomenon allowing a rise in temperature. The experimental set-up allows the temperature and force to be monitored and recorded in real time. During the test, significant vibrations are generated, that induce fluctuations in the measured axial force.

The following parameters are used: rotational speed of 3000 rpm, stabilized average axial force of 465 N, total duration of 500 s. Thus, the thermocouple measures a maximum temperature of 383 °C (Fig. 4) which is approximately equal to 60% of the melting temperature and therefore within the mid-hot forging range [10]. Fig. 5 shows marks left by the tool after an operation.

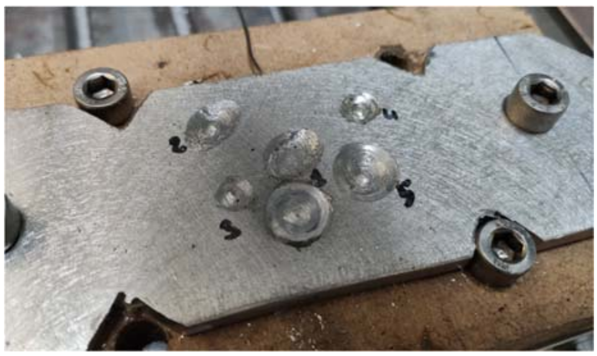

Fig. 5 Substrate after a series of tests

C. Recalibration of the Numerical Model and Results

The experimental protocol imposes that the application of the axial force is progressive from 0 to the attempted value. This assumption was added to the simulation afterwards. Fig. 6

shows the temperature distribution in a section of the tool and the rod after a sequence of 500 s with a rotation at 3000 rpm and under an axial force applied as follows: progressive increase to 465 N between 0 s and 180 s and constant between 180 s and 500 s.

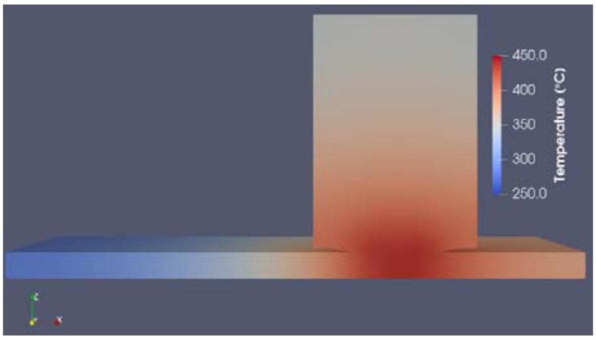

Fig. 6 Temperature distribution in the system, under 3000 rpm and 465 N (with ramp) during 500 s

IV. Discussion

In order to go further in the definition of a process window, sensitivity of temperature rise phase to axial force and rotational speed is studied using the numerical model.

A study on the impact of the rotation speed shows that the temperature field increases almost linearly with the increase of this parameter (Table II, Fig. 7). Doubling the rotational speed increases the maximum temperature reached at the friction interface by a factor of 1.8. Another study on the impact of the axial force (Table II, Fig. 8) allows to observe that doubling this parameter impacts the maximum temperature reached by a factor close to 2. Moreover, axial force and rotational speed both affect the time required for the system to reach a threshold temperature considered to be around 75% of melting temperature to meet hot forging requirements [10].

TABLE II
Testing the Influence of Rotational Speed and Axial Force on Temperature

No	Rotational Speed (rpm)	Axial Force (N)	Duration (s)	T°max (°C)
1	500	465	580	98
2	1000	465	580	175
3	2000	465	580	320
4	3000	465	580	470
5	4000	465	580	620
6	5000	465	580	770
7	3000	100	580	100
8	3000	200	580	195
9	3000	300	580	310
10	3000	400	580	410
11	3000	500	580	500
12	3000	600	580	600

An objective of numerical simulation other than that of predicting the temperature rise time of the system subjected to a precise parametric set is to be able to estimate the temperature where it cannot be measured. Thus, the temperature measured at the thermocouple will allow to know the temperature at the friction interface and to determine in which phase the filler metal is located, to continue the temperature rise phase, or to pass to the deposition phase.

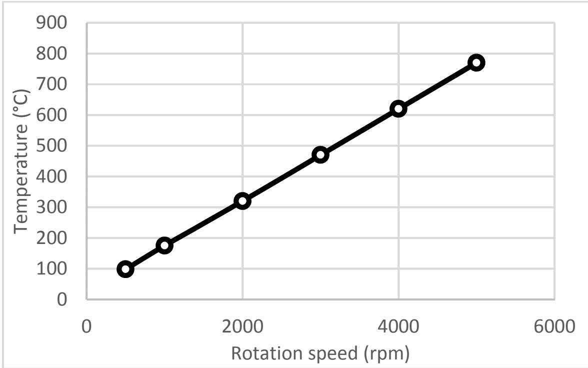

Fig. 7 Influence of the rotation speed on the temperature

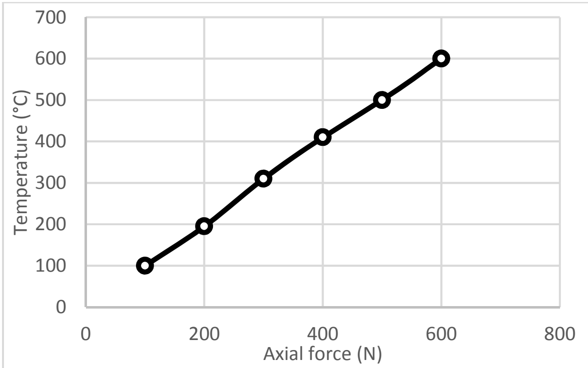

Fig. 8 Influence of axial force on temperature

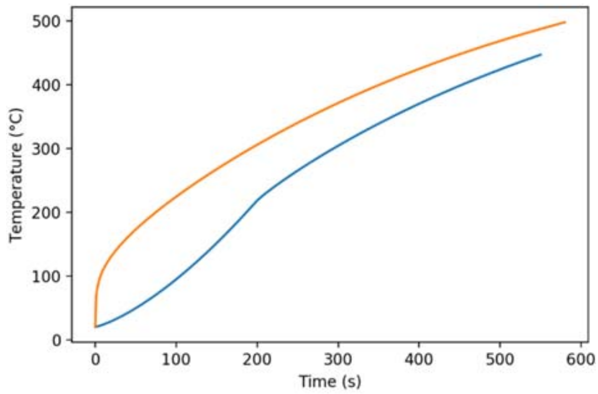

Fig. 9 Difference between application of a force ramp (blue) and a step application of the force (orange)

During the tests, the force is increased progressively to the target value because of the vibrations induced at the contact interface. The model is modified to include this phenomenon. Fig. 9 shows the difference between the application of a force ramp and a step of force. In the second case, the elevation of the temperature is slower than in the first case and the temperature curve exhibits a horizontal tangent at the beginning, sign of the progressive application of the axial force. This difference is characterized by a higher maximum temperature in the first case than in the second case.

To reproduce the experimental conditions in the simulation, it is important to consider the application of the force per increment (visible in Fig. 4), as well as its drop during the test. In this way, the temperature at friction interface during experimentation is estimated around 450 °C, i.e., 68% of the melting temperature of aluminum (Fig. 10). Fig. 4 shows the impact of the force on the temperature rise rate; the temperature rises faster when the force increment increases.

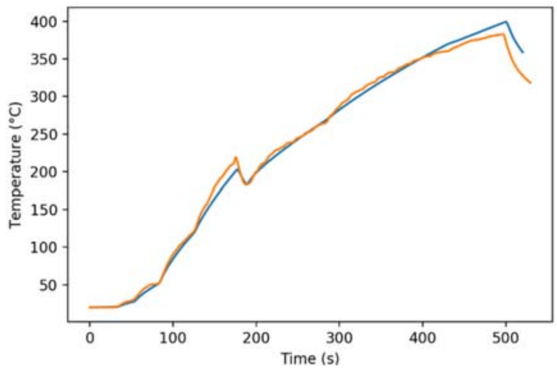

Fig. 10 Comparison of temperature curve during experimentation (orange) and numerical simulation (blue)

The comparison of the temperature curves from the different numerical simulations with the experiments validates the usefulness of the numerical model in estimating and analyzing the sensitivity of the maximum temperature reached to the operating parameters. Numerical simulation of ideal parameters coupled with practical limitations observed during experiments allows the definition of a process window meeting two objectives: to estimate temperatures reached at any point in the system, including areas such as the friction interface where measurement is not possible, and to define parameters that are experimentally usable with the technical constraints of the process.

One limitation of this initial friction model is that the dynamic friction coefficient is considered constant although the temperature varies over time. Studies [12]-[14] prove that friction coefficient is a function of temperature and contact pressure.

V. Conclusion

This study deals with an innovative process using friction for material deposition, in which there is a temperature rise phase followed by a material deposition phase. This work focuses on the understanding of the parameters influencing the temperature rise phase. A numerical and experimental study is carried out on the docking phase of the friction stirring tool on the substrate. This phase allows the system (composed of the tool, the filler metal, and the substrate) to rise in temperature in order to allow the deposition of the material in a second phase. The understanding of the physical phenomena inherent to the process is therefore essential. Numerical modeling provides an interesting tool to reach that goal.

In the first part of this research, numerical simulation is used to derive an initial set of operating parameters. An experiment using a robotized effector dedicated to the process is then carried out with the chosen axial force and rotational speed. After 500 s, a peak temperature of 385 °C was measured on the aluminum substrate approximately 10 mm far from the friction zone. Due to vibrations induced at the friction interface, the application of the axial force required to be smoother than considered initially. Numerical model was thus adjusted to include progressive increase in axial force, and a very good correlation was obtained between measured and predicted temperature, allowing an accurate estimation of temperature in the contact zone.

Numerical analysis of axial force and rotational speed influence on the temperature reached at the friction zone was finally performed, leading to the identification of a theoretical process window for the temperature rise phase.

Future work will focus on increasing the fidelity of the model by considering the evolution of friction coefficient with temperature and contact pressure.

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