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Shear coefficient determination in linear friction welding of aluminum alloys

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ABSTRACT

In the present study, a combined experimental and numerical investigation on Linear Friction Welding (LFW) of AA2011-T3 aluminum alloy was carried out in order to find the temperature dependent shear coefficient to be used in a 3D numerical model of the process. Torque, oscillation frequency and pressure were acquired in order to calculate the shear stress at the interface. A numerical thermal model was used to calculate the temperature at the interface between the specimens starting from experimental temperatures acquired through a thermocouple embedded in the LFW specimens. Finally, the calculated shear coefficient was used to model the contact between the two specimens in a dedicated 3D, Lagrangian, thermo-mechanically coupled rigid-viscoplastic numerical model of the LFW process. A narrow range of variation of the shear factor vs temperature curve was found with varying LFW process parameters and good agreement was obtained for the temperature prediction of the 3D model of the process.
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1. Introduction

Linear Friction Welding (LFW) is a solid state welding process used to join bulk components. As a friction welding processes, solid bonding is obtained from the mechanical work decaying into heat in order to create a softened material which can be mixed and effectively joined. Different techniques can be used to create the needed frictional heat and consolidate the weld. Friction Stir Welding (FSW), the most recently introduced friction based welding process, is used to weld sheets in different configurations (butt, lap, T, etc.) [1–3]. A properly designed rotating tool is plunged between the adjoining edges of the sheets to be welded, producing the needed heat by friction forces work, while the stirring action of a pin induces the material flow. Rotary Friction Welding (RFW) and Inertia Friction Welding (IFW) [4] are used to join axisymmetric parts with particular reference to tubes. In the process, one tube is put into rotation and the other, inhibited from rotation, is forced against the former. No tool is needed.

In LFW, a reciprocation motion is generated between two bulk components and a forging pressure is applied in order to provide the needed heat input at the interface between the two parts to be welded [5,6]. Although the process was first patented by Walther Richter (Germany) in 1929 [7], no actual application or research activity was developed as the description of the motion was very vague and the process was labeled by Vill (Russia) in 1959 as "very doubtful". A considerable interest was shown by different industry sectors, but machines were considered too expensive. Reliable and lower cost machines were first developed in late 1990s. From that date, an increasing interest both in the academic and industrial fields was observed for LFW.

As the other solid bonding based techniques, LFW shows distinct advantages over traditional fusion welding processes, i.e. possibility to weld "unweldable" or difficult to be welded materials, absence of fumes, better material microstructure, joint integrity due to reduced grain size in the weld zone as well as lack of inclusions and porosities [8].

As far as LFW process mechanics [5] is regarded, the two materials are first brought in contact under pressure. At this stage, the two surfaces touch each other on asperities and the heat is generated from solid friction. Surface contact area is expected to increase throughout this phase with the reduction of asperities height. The heat input must be larger than the one lost by radiation or insufficient thermal softening occurs inhibiting the contact area to reach 100%. At this phase, instabilities can appear due to non-uniform temperature distribution at the interface or due to geometrical imperfections of the specimens. If sufficient heat is provided, the material is extruded from the four edges of the specimens and a reduction in height is observes. Finally, as the desired upset is reached, the reciprocating motion is stopped very quickly, i.e. in less than 0.1 s, and an increased forging pressure is simultaneously applied to consolidate the weld [9,10].

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Main process parameters are the pressure superimposed on the specimens to be welded, the frequency and the amplitude of oscillations of the specimens and the time length of the operation. These parameters must be properly determined for each base material to be welded in order to reach proper bonding conditions and to maximize the mechanical performances of the produced joints.

Several metal materials can be considered in the LFW process, namely steels [11,12], stainless steels [13], nickel based superalloys [14], titanium alloys [9,15], copper [16] and aluminum [17]. LFW of aluminum alloys can be very attractive for the possibility to weld with high efficiency aeronautical and aerospace aluminum alloys, namely AA2XXX and AA7XXX, in monolithic configurations. At the moment, very few applications of LFW of aluminum alloys are known. Rotundo et al. [18] demonstrated the feasibility of Dissimilar linear friction welding between a SiC particle reinforced aluminum MMC and AA2024, finding good tensile and fatigue properties, with respect to the AA2024 base material. In [19] the authors analyzed LFW joints obtained out of similar AA2024 specimens, finding joint efficiency of about 90%. In [20] Jun at al. obtained the residual strains in AA2024/AlSiCp linear friction welds, using a novel approach based on eigenstrain. Song et al. [21] studied the residual stress distribution in AA2024-T351 using both experiments and numerical simulation. Finally, Fratini et al. [17] studied LFW of AA6082-T6 aluminum alloy finding a process window depending on oscillation frequency and pressure. The lack of knowledge regarding LFW of aluminum alloys is also due to the difficulty in finding proper process parameters because of the material thermo-mechanical characteristics, namely thermal conductivity and heat capacity. The high thermal conductivity of these materials imposes that high heat must be input into the specimens in a reduced time, which is usually two to four time shorter than the one used for steel and titanium alloys. Consequently, large oscillation frequency values must be used to produce sound welds.

FEM can be an effective tool for the process design. As a matter of fact, due to the need to take into account, at the same time, technological, geometrical and metallurgical variables, the use of a numerical model can be very useful in the engineering of LFW of aluminum alloys. A reliable FEM model of the process can be used both to fully understand the process mechanics and to predict the actual bonding of the specimens through proper bonding criteria [22]. A few papers can be found in literature focusing on numerical simulation of LFW [23]. Most of the numerical models in literature, developed for titanium alloys, use a 2D approach with one of the two specimens modeled as a rigid-viscoelastic or elasto-plastic object and the other as a rigid one [24–26]. Li et al. [27] modeled the LFW of TC4 titanium alloy by a combination of explicit and implicit finite element analysis to study the influence of the main process parameters on axial shortening and temperature distribution. Song et al. [21] used a 2D approach with both specimens modeled as deformable objects to predict the residual stress in AA2024 LFW welds. A dedicated remeshing algorithm was used to take into account the large strain accumulated in the flash area. Recently, McAndrew et al. [28] used a novel approach, based on a single deformable body model [25]. The process is modeled starting by the onset of sticking friction, i.e. when the contact surface between the specimens is about 100% of the contact area and a viscous material flow is generated at the interface. Very good results can be obtained in terms flash morphology prediction and surface contaminant removal. However, an experimentally measured temperature field, taking into account the prior stages of the process, must be given to the model as initial condition. For most of the cited papers, a temperature depending shear coefficient was used to model the contact between the two specimens to be welded. It is worth noticing that this aspect is crucial in order to develop a reliable numerical model of the process. However, for none of the above cited papers details were provided on the determination of the shear coefficient curve.

In the paper, a combined experimental and numerical investigation is carried out on LFW of AA2011-T3, a high mechanical strength aluminum alloy used in the transportation industry for its excellent machinability, with the aim to determine the shear coefficient to be used in the numerical model of the process. It should be observed that this structural alloy is characterized by extremely poor weldability and thus welding is not recommended by traditional fusion welding techniques. In order to develop the experimental campaign, a previously in-house designed and built LFW machine was equipped with a number of measuring sensors [11,17]. Different tests were carried out with varying pressure and oscillation frequency. The data measured during the tests were collected and used to obtain the shear stress at the interface between the two specimens. Numerical results coming from both a pure thermal model and a thermos-mechanical model of the process were used to calculate the shear yield stress at the interface starting form experimental temperature measurements. Finally, the friction coefficient m as a function of process temperature at the interface was determined and validated using the 3D, thermo-mechanically coupled numerical model of the LFW process. In this way, an enhanced numerical model was obtained permitting to increase the accuracy and the quality of the acquired information.

2. Experimental approach

2.1. LFW machine

An in house developed experimental machine was used to carry out the experiments [17,29]. This machine uses a desmodromic kinematic chain in order to generate the oscillation motion of the bottom specimen. Two interchangeable cams with three lobes were chosen in order to widen the available range of oscillation frequency. The cams were assembled on two parallel shafts connected by coupling belt and pulleys [29]. An hydraulic actuator, fixed on a steel rack and controlled by an electro-valve, allowed to apply on the top specimen a pressure up to 250 MPa. A pneumatic clutch, activated by an electro-valve, and a micro-switch were used to control the start and finish of each experiment through a virtual instrument interface.

A number of devices and sensors, controlled by a unique interface, were introduced to increase the machine capabilities. A speed–torque meter was used on the secondary shaft to measure the required power and a fly wheel was adopted to balance the effects of inertia. A sketch of the main components of the machine is shown in Fig. 1.

A K-type thermocouple was fixed to the top specimen, at a distance of 6 mm from the specimens interface, to measure the temperature histories. All signals were conveyed to a National Instruments DAQ Card 6062 12 bit 500 kSa/s by means of a BNC-2120 connector and analyzed by a proper routine programmed with LabVIEW. The clutch was controlled by a pneumatic SMC solenoid valve and activated by the Labview interface. The clutch has the important function to obtain a quick stop reducing the machine inertia [20]. The software allowed to control the machine and monitor the process variables during and after the developed tests from a unique front panel.

2.2. Developed tests

The specimens, machined out of AA2011-T3 aluminum alloy bars, are characterized by height of 10 mm and cross-sectional dimensions at the contact interface equal to 10 mm × 7 mm.

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