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Effective Linear Friction Welding Machine Redesign through Process Analysis

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Abstract. Linear friction welding is a solid-state joining process developed for non-axisymmetric components in which the joining of the specimens is obtained through reciprocating motion and pressure. In the process, the friction forces work due to the high frequency oscillation and the pressure between the specimens is converted in thermal energy. In order to design an effective machine, relevant issues derive from the high frequency and the large inertial forces involved in the process. In this study, the authors describe the redesign of a preexisting prototypal machine for LFW processes. A machine redesign is needed when welding high resistant materials, i.e. steels or titanium alloys, with high frequencies, up to 72 Hz. The sensors equipping the machine allows in process measurements of key process variables as temperatures of the specimens, tangential forces, accelerations and speeds. At the same time through the acquired data, the main weaknesses of the machine can be highlighted allowing for effective redesign.

Introduction

Solid state welding is gaining an increasing interest among the scientific and industrial community because of the advantages it allows, over traditional fusion welding processes, in terms of joint quality and range of weldable materials. In friction based solid-state welding processes the needed heat is produced by the friction forces work, generated in a few different ways. As Friction Stir Welding (FSW) is considered, a properly designed tool is used in order to generate heat and mix the material; in turn, in Rotary Friction Welding (RFW) and Linear Friction Welding (LFW), the parts to be joined generate the heat needed through rotational and reciprocating motion, respectively. During LFW, a stationary part is forced against a part moving with reciprocating linear [1,2]. Due to the heat input and the pressure applied at the welding interface, the material in this area is softened and deformed. Most of the plasticized material is removed from the joint in form of flash, extruded by the combined action of the applied force and the linear oscillation. Surface oxides and other impurities are removed through the flash, allowing an intimate metal-metal contact between the specimens.

Some advantages of the process include the minimal or no preparation of the surfaces to be welded; the rapid and automatic cycle does not require specialized figure; heating is obtained in a uniform manner around the weld that occur without distortion and without the introduction of internal tensions [1],[3]. Filler materials are not needed and, since the process is self-regulated, costly quality control procedures can be simplified.

During the process four distinct phases can be identified [4,5]. During the "Initial Phase", the two parts in reciprocating motion are brought into contact under an assigned pressure. Contact will be obtained on surface asperities, and heat is generated by friction between the parts . The real contact area increases significantly during this phase due to roughness reduction. There is no axial shortening of the samples at this stage. If the rubbing speed is too low for a given axial force, the heat generated by friction is insufficient to compensate the conduction and radiation losses, insufficient thermal softening is reached and the next phase cannot occur.

The second phase is called “Transition Phase”. If sufficient heat has been produced during the previous stage, the temperature at the interface increases and the resistance of the material decreases. Specimens material begins to be expelled from the interface and the heat affected zone expands. The actual contact area is considered 100% of the cross section, and the plasticized layer between the two materials is no longer able to support the axial load.

The following phase is called “Equilibrium Phase”. The hot plasticized material is extruded from the interface in form of flash due to the concurrent action of the oscillatory motion and the applied pressure. Significant axial shortening of the workpieces occurs because of the ejected material. The heat generated by the breaking and reformation of the bonds contributes to increase the extension of the plasticized zone. Instability may appear during this stage, due to incorrect choice of the process parameters. If temperature increases too quickly due to too high oscillation frequency and/or pressure, the material is over softened, an excess of flash is extruded and the specimen collapses under the applied pressure resulting in failure of the welding process [6].

The Final phase is called “Deceleration Phase”. When the desired upset is reached the oscillation is stopped very rapidly (in less than 0.1 s) [7], and forging overpressure may be applied.

It is therefore clear that there is both a lower and an upper limit of input power that must be provided. If small values of interface pressure, oscillation amplitude and/or frequency are used, the material will never reach the needed conditions to have a correct solid bonding.

In order to carry out the process, a few input variables must be set:

- Frequency: number of cycles per second oscillators.
- Amplitude: maximum oscillating movement of the piece from its equilibrium position.
- Interface Pressure: pressure applied during all the phases of the process. This pressure is calculated using the nominal contact area at zero amplitude.
- Distance of Burn-Off, Time or Cycles: fixing one of these parameters the process duration is determined.
- Deceleration Time: time to reduce to zero the scale before the beginning of the forging phase.
- Forging Pressure: the pressure applied during the forging phase.
- Forging Time: the amount of time during which pressure is applied when the oscillation is stopped.

Other important parameters are a consequence of the main input variables and cannot be easily changed through the variation of the main variables:

- Upset: the loss of the total length (shortening) due to the process (the upset will always be higher than the distance of burn-off mainly due to the loss of length occurring during the forging).
- Friction Force: force parallel to the oscillatory movement.
- Burn-Off Speed: shortening velocity , i.e. the gradient of the curve of burn-off.

In this paper, the authors describes the key aspects of the design process of a LFW machine. A kinematic analysis was performed in order to evaluate the influence of the clearance of the desmodromic system on the oscillation effectiveness. The used instrumentation was used to identify the machine limits in terms of maximum welding pressure.

LFW machine

Fig. 1a shows a sketch of the developed machine [8]. A unique feature of the developed machine is that the reciprocating motion is obtained through a *desmodromic system*. This system consists of two cam-plate mechanisms, placed at the ends of the oscillating parts [9]. Two toothed pulleys are fixed on the two parallel camshafts (Fig.1b) in order to allow the motion transmission and the correct phasing between the two cams. Multi-lobe profiles were used for the cams in order to increase the range of oscillation frequencies. The bottom specimen holder is located between the two followers. Two preloaded springs, preventing sudden machine failure due to the incorrect cam phasing, are interposed between the plates and the bottom specimen holder.

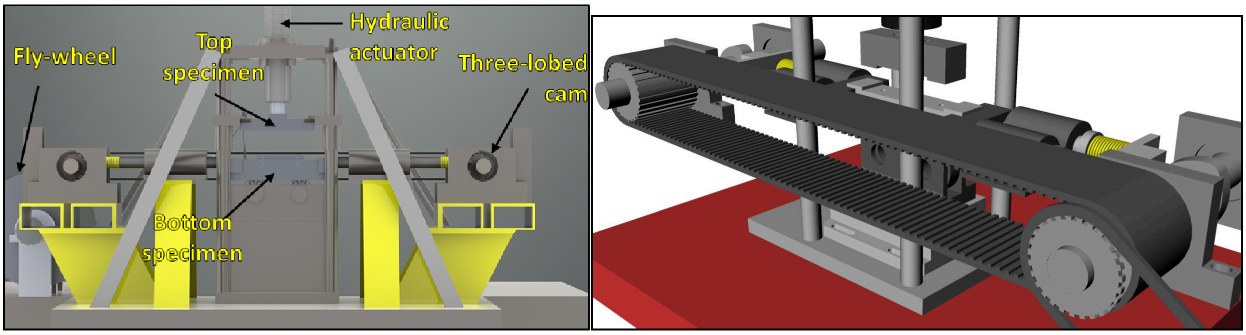

Figure 1. (a) Sketch of the machine and (b) close up pf the Toothed transmission belt

The top specimen is fixed to a hydraulic actuator capable of ensuring loads up to 15000 kN. An appropriate steel frame supports the system. The hydraulic actuator is connected to a hydraulic circuit providing the needed pressure between the specimens. A gear pump, able to ensure a pressure in the circuit ranging from 0 up to 25 bar, is used. The driving motion is taken from a lathe through a transmission trapezoidal belt. The belt is connected to the lathe by a pulley fixed on the lathe spindle, while it is connected to the LFW machine by another pulley fixed to a camshaft. In order to transmit the desired power, the pulleys have a double groove profile.

In order to avoid direct coupling between the lathe and the LFW machine, an intermediate shaft was utilized. In this way, the resistant torque variations coming from the LFW machine are not transmitted directly to the lathe. As a matter of fact, the resistant torque is variable in time and the torque peaks, resulting from a possible malfunction of the machine, are perceived by the lathe causing serious damage.

The additional shaft was connected between the lathe and the LFW machine. On the shaft, the following devices have been fixed:

- A double groove pulley, utilized to derive the power from the lathe;
- A fly-wheel, used to stabilize the resistant torque perceived by the lathe;
- A speed-torque meter, ("before" the fly-wheel in the kinematic chain) to measure the torque and the rotation speed of the intermediate shaft in order to assess the power absorbed by the machine;
- A pneumatic clutch, ("after" the flywheel in the kinematic chain) to allow the instantly stop of the reciprocating motion of the LFW machine.

The cams have a trilobe profile (Fig.2) able to increase the range of oscillation frequencies available.

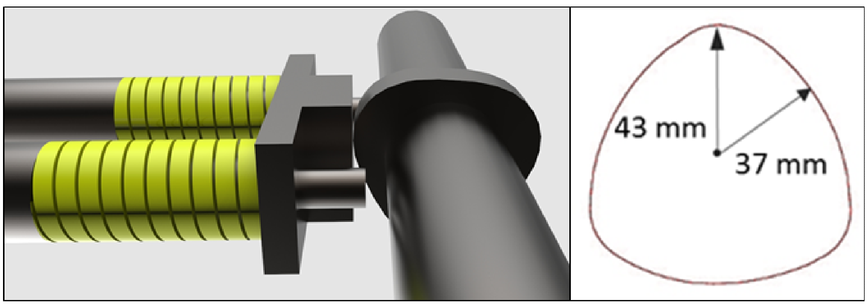

Figure 2. CAD and geometry of Three-lobed cam

The machine was equipped with a few measurement devices. In particular a Piezoelectric accelerometer (Bruel & Kjaer type 4370, range 0-6 kHz, 2000 g), an extensometer torsio achymeter (Tekkal TT-4000, range 0-200 Nm, 0-4000 rpm), a digital pressure gauge for the oleodynamic circuit and a thermocouple (K type) were connected to National Instruments acquisition card (DAQ Card 6062 12 bit 500 kSa/s) in order to create a unique control panel for the process. Fig. 3 shows the measurement device together with the designed control panel

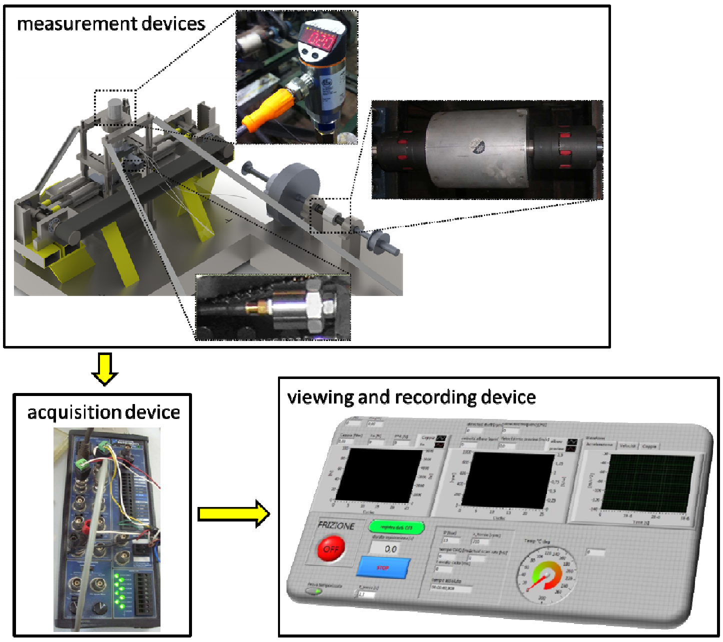

Figure 3. CAD and geometry of Three-lobed cam

Machine Analysis

Although an ideal desmodromic distribution has a clearance equal to zero, in practical applications a non-zero clearance value is needed. The introduction of the clearance results in a modified oscillation with respect to the expected theoretical one. In the developed machine, the oscillation amplitude is controlled by the cams geometry. Once the cam profile is fixed, the stroke of the reciprocating motion is determined. During this study, the selected cams allow for a maximum stroke of 6 mm (oscillation amplitude 3 mm). The frequency of oscillation will be determined by the speed of rotation of the cam. The ideal oscillatory motion will be given alternately by two cams, that will be assembled with a certain phase angle so that the phase of raising of a corresponds the return phase of the other or vice versa.

The motion equation of the plate-cam (1) respect to the rotational joint O_1, has the following expression (Fig.4):

$$O_1C = R_b + s(\vartheta) \tag{1}$$

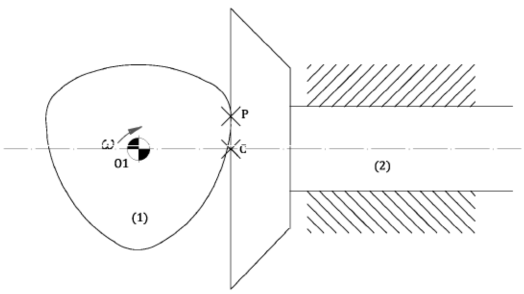

Figure 4. Real cam-plate contact

Where C is the point on the normal at the plate passing through the cam rotation center; Rb is the minimum cam lift and s(θ) is the plate angular position. It is worth noticing that eq.1 is valid only if the closure force is guaranteed and in this specific case is alternatively ensured by the two cams.
For the kinematic analysis of the actual machine, two assumptions were introduced:

- The safety preload springs are rigid objects, i.e. no unwanted overload is present;
- Rotational speed and relative cam position are constant.

The real machine meets these last assumptions. In fact, the real welding process starts only when the machine has reached the predetermined rotation regime and not during transients.

As briefly described, in the actual configuration a clearance is needed. When cam (2) reaches the maximum lift, the cam is still in contact with the corresponding plate but is no longer able to move the plate. At the same time, cam (1) is not yet in contact with the respective plate but has the same angular velocity of the cam (2) thus maintaining the correct phase with respect to it. According to the mechanism scheme, the oscillating object (3) has the potential to continue its motion toward cam (1) due to the inertial forces, and impacts with the cam (1). However, in the LFW process, after cam (2) detaches from the oscillating object (3), the velocity of the latter is zero due to the resisting forces at the interface between the specimens to be welded. In other words, the oscillation instantly stops once the contact with the cam ceases. In Figure 5, the position of cam (1) before and after the clearance recovery is reported:

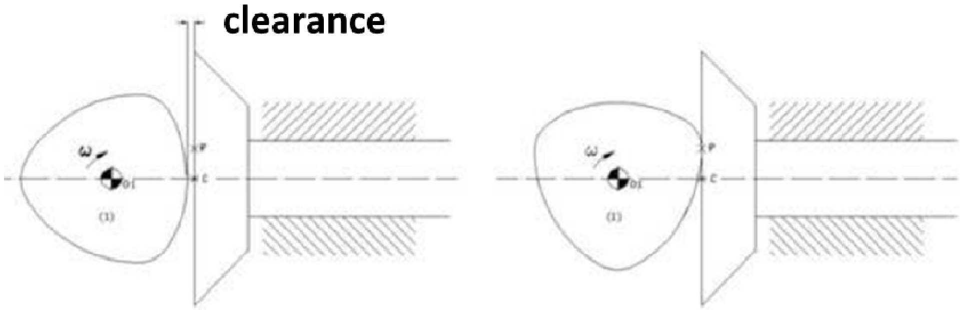

Figure 5. Clearance recovery

Assuming cam (1) as the driving one, the distance between O1 and P constant (since the plate is stopped) and finally indicating with the subscripts "a" as initial phase and "b" as final phase of the mechanism, it is possible to write:

$$O_1P_a = O_1P_b \tag{2}$$

$$R_b + gap = R_b + displ._b \tag{3}$$

but also it is possible to hypothesize that:

$$displ._b = clearance$$

Therefore, cam (1) resumes contact when the plate displacement required is equal to the initial clearance. From the "b" phase on, cam (1) will cause the displacement as if no clearance was present. Finally, when cam (1) gives the maximum lift, cam (2) will be found at the minimum lift point. Based on these considerations, it is possible to perform a numerical analysis studying the kinematic and dynamic mechanism. The equations used are the ones of the mechanisms without clearance. There is contact between the cam and the plate, while during the recovery phase of the clearance, lift (h), velocity (h’) and acceleration (h’’) are zero because the plate is stationary. The equations governing the oscillation with no clearance are:

$$h = \frac{h_{max}}{2} \cdot [1 - \cos(n\theta)]$$

$$h' = \frac{n}{2} \cdot h_{max} \cdot \sin(n\theta) \tag{4}$$

$$h'' = \frac{n^2}{2} \cdot h_{max} \cdot \cos(n\theta)$$

In the equations shown, h_{max} is the maximum lift of the mechanism, n is the number of cam lobes, θ is the rotation angle of the reference cam. h' and h" are Lagrangian derivatives with respect to the variable θ. The relationship between the Lagrangian derivative and the time derivative is the following:

$$\dot{h} = \omega \cdot h'$$

$$\ddot{h} = \omega^2 \cdot h''$$

Where ω is the cam rotational speed expressed in rad/s. MATLAB was used to carry out the numerical analysis. In the script, the following parameters were varied:

- Maximum lift
- Clearance
- Number of lobes
- Base radius
- Rotational Speed

The mechanism kinematics was studied including the effect of the real clearance of the machine, i.e. 2.2 mm. A cam rotational speed equal to 710 rpm was imposed.

From Figure 6, it can be clearly seen that lift is quite different from the ideal one, i.e. a perfect sinusoid.

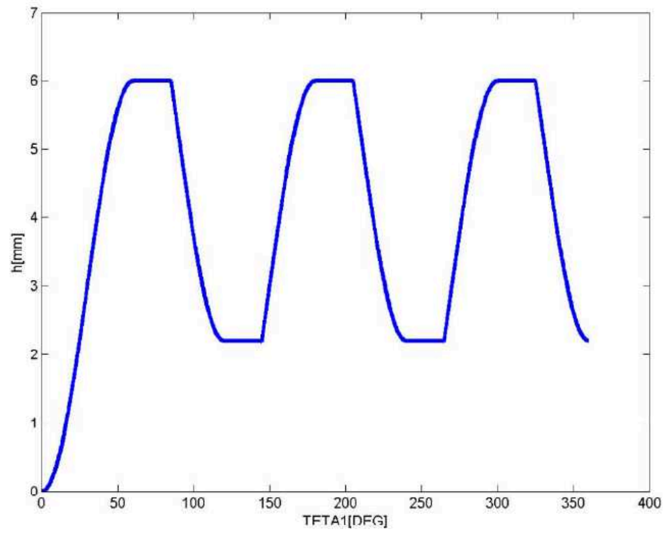

Figure 6. Cam (1) lift Vs rotation angle θ1 – clearance=2.2mm

The oscillating object remains stationary for a certain period. This period is proportional to the initial clearance value. Therefore, the difference between maximum and minimum lift is decreased by an amount equal to the initial clearance. In this way a break, not present in the ideal diagram is introduced in the lift diagram. It is possible to evaluate the influence of the clearance through the calculation of effective value of the defined speed, as

$$h'_{rms} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} [h'(\vartheta)]^2 d\vartheta} \quad (5)$$

Eq.12 calculates the effective value of the Lagrangian velocity of the oscillating object. This value will be affected by the clearance. Figure 7 shows the influence of the clearance on the effective Lagrangian velocity (h'rms).

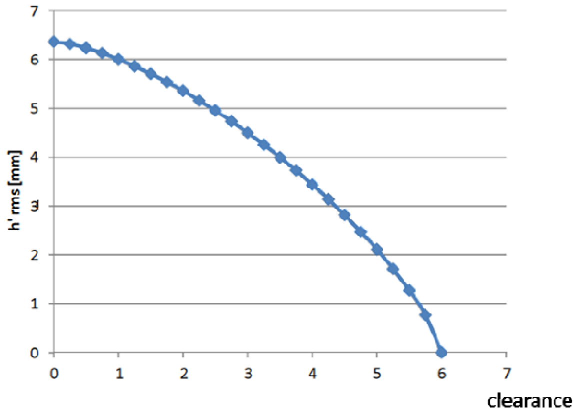

Figure 7. The effective Lagrangian velocity (h'rms) Vs clearance

Form the above figure it is noted that, with increasing clearance, the effective speed value decreases. When the clearance is equal to 6 mm, i.e. the theoretical value of the oscillation amplitude, an effective velocity equal to zero is obtained. This means that no welding can be produced. In turn, when the clearance is equal to 2.2 mm, the effective velocity is about 5.2, corresponding to 84% of the ideal value. In this way, it can be evaluated if the clearance used results in acceptable loss of effectiveness of the effective Lagrangian velocity.

When welding high resistant materials, effective Lagrangain velocity can further decrease due to insufficient stiffness of the structure on which the hydraulic actuator and the top specimen are fixed. This can be evaluated through the accelerometer. If large tangential forces are transmitted from the bottom oscillating specimen to the top specimen, the entire structure will oscillate thus significantly compromising the relative motion between the specimens. A schematic representation of this phenomenon is showed in Fig. 8. The developed machine is able to withstand maximum pressure applicable of 83 MPa [10].

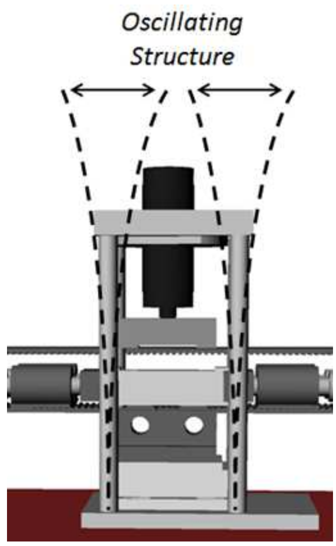

Figure 8. Motion of top-specimen

Conclusions

A machine was designed and built in order to carry out Linear Friction Welding experiments on lab size specimens of light alloys. A desmodromic system was selected in order to obtain the desired values of oscillation frequency. A proper hydraulic circuit was used in order to give a wide range of pressure on the top specimen. The machine was equipped with a few sensors in order to measure applied force, absorbed torque and actual oscillation. The influence of the clearance on the effective oscillation velocity was evaluated in order to identify the detrimental effects on the oscillation due to insufficient stiffness of the structure. In this way, the machine limits could be identified. From the obtained results it arises that the developed machine allows correct welding of light alloys as aluminum alloys.

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