SHEET FORMAT STEEL FLASH-BUTT WELDING VARIABLES INQUIRY FOR MATHEMATICAL MODELING

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Abstract: *Modelling Flash-Butt welding process using mathematical tools is proposed. It is a complex thermo-electro-mechanical and phase transformation problem. Consecutive stages (sub-processes) are defined, where mathematical variables can be distinguished. Some hypothesis are defined; however, more research is needed to complement those simplifications. The relationship between the whole process, the technical considerations and the proposed mathematical variables is studied. Heat diffusion equation is proposed as a governing equation for model de temperature profile evolution on each phases; phase transformation it is not contemplated yet.*

Key words: *Flash-Butt Welding, Mathematical Modeling*

1. INTRODUCTION

For automotive and aircraft industries, increasing energy efficiency and reducing emissions levels maintaining quality parameters and safety criteria have been turned a priority necessity; new generation structural frames are built using Advanced High Strength Steels (AHSS) which are stronger (more toughness) and lighter than older ones. At any application/fabrication stage of them, welding processes should be required; unfortunately, these steels suffer poor weldability, presenting brittle behavior when not appropriate welding conditions. On Flash-Butt (FB) welding, tuning process variables is a complex issue, reason why it should be needed a mathematical modelling for future computational simulation, in order to provide optimal tuning of welding parameters/variables. This paper presents the involved possible variables into sheet steel format FB welding process, in order to run on future works, a proper mathematical model.

2. METHODOLOGY

FB welding is an intricate process to model, especially when including steel thermo-mechanical behavior and phase transformations. Technological Segregation Methodology (TSM) helps to manage the problem; it is possible to separate the complete process on subsequent small processes, and these again on subsequent simpler sub-processes or stages.

Four principal processes could be distinguished: 1.- Steel fabrication process, 2.- Pre-welding, 3.- FB welding, and 4.- Post-welding. First process defines steel chemical composition, initial physical properties, and the Base Metal (BM) region. Ichiyama (2007) recommends the Second and Fourth process, in order to mitigate brittleness on welding. Third process (the focus of the inquiry) is decomposed into sub-processes or stages shown into next sections.

After definition of these variables, a mathematical governing relation is defined: Heat Diffusion Equation.

3. DEFINITION OF VARIABLES

3.1. Steel fabrication process

It is not intended to focus on steel fabrication process, this information can be obtained on literature; emphasis results on analyze mathematical variables involved on this process, variables that could affect welding.

Chemical composition (alloying elements) rules steel behavior. A first hypothesis can be stated assuming that there would not be any kind of contamination or mass losing disturbing alloy proportions: *"Chemical composition is constant on the whole process (from 1 to 4); and thermo-eletro-physical properties may vary according constitutive chemical elements organization (formation of microstructure/morphology according transformation processes)"*. Contamination and mass losing exist, especially when welding; but for an initial modeling approach, they can be neglected.

Literature shows an enormous information platform about steel chemical composition; present paper skips the analysis for each alloying element. It is impractical to think about establish a mathematical variable to each alloying element; Landcaster (1999) states that a common practice for managing all alloying elements concentrations in a single expression is to use the equivalent Carbon content expression; actually, it depends on steel type, application and welding type. Accordingly, with these criteria a main variable that could affect welding is defined: **Equivalent Carbon content** ($CE\%$), measured by weight.

Steel fabrication process affects the mechanical behavior of steel, depending of its nature, different kind of variables can be established. Accordingly with Ichiyama et. al. (2016) there are a strong relation between Martensite content and steel´s hardness; in order to simplify the first modelling approach, a generic variable is defined: **Martensite volume fraction** (M_i%). This variable can be measured for most AHSS, and it can be related easily with brittlening (coupled with hardness). After welding M_i% may vary, with/without heat treatment (Pre or Post) it permits quantitative comparisons.

Therefore, mechanical variables, related to M_i% can be defined: **Initial Yield Strength** (σ_{Y_i}), **Initial Ultimate Strength** (σ_{U_i}) and **Initial Hardness** ($H\#_i$) (i.e. DP600 steel: $\sigma_{Y_i} = 400\ [MPa]$; $\sigma_{U_i} = 600\ [MPa]$; $HB_i = 170$). Thermal variables are not strongly related to M_i%; for a first modelling approach a second hypothesis can be stated: *"Each thermal variable would be independent of material (position from one pivot point), time and temperature profile".* **Thermal Conductivity** ($k_{(\bar{x},t)} \cong k$), **Specific Heat** ($c_{p(\bar{x},t)} \cong c_p$) and **Density** ($\rho_{(\bar{x},t)} \cong \rho$). For more accurate modelling, and a realistic representation these approximations need more research.

3.2. Pre-welding

This second process resumes on Pre-heating. Ichiyama et al. (2007) proves that certain quantity of heat input before FB welding process allows better conditions for flashing and pressing stages, improving weld toughness. Those benefits can be explained mathematically (explanation consists on reduce temperature gradients, avoiding non-beneficial thermal stresses); with this purpose, **Pre-heating heat input** (E_0) is defined as a variable that affects brittleness on welded regions.

3.3. Flash-Butt welding

<u>Squeezing or Clamping</u>: FB welding machine forces a high magnitude electric current to flow through workpieces welding edges. One edge is firmly clamped in the stationary electrode (fixed electrode), the other edge in the cooperative electrode; a relative movement exist between the two electrodes when forging, cooperative electrode is mobile. An initial separation exist on clamping stage, when flashing and when forging this separation is reduced; some variables (in practice they turn constants values) can be defined: **Initial electrode separation** (d_0) (distance on clamping, initial distance between dies), **Flashing upsetting distance** (d_F) (from d_0 to d_1) and **Pressing upsetting distance** (d_P) (from d_1 to d_2), where d_1 is **Intermediate electrode separation**, d_2 is **Final electrode separation**. Note that: $d_0 > d_1 > d_2 > 0$.

On contact surfaces between electrode and workpiece, exist a contact electric resistance, which need to be small enough to extend electrode work life. Poor electric contact promotes micro electric arcs formation between workpiece and electrode contact face, this fact wears electrodes because of cooper electrodes are weaker than steel workpieces when micro electric arcing corrosion. An **Electrode-workpiece contact resistance** mathematical variable is defined for each electrode (R_{C1}, R_{C2}); it can be supposed that contact resistance from both clamps are mostly the same, one variable (can be assumed as a constant value) can represent contact resistance (R_C).

<u>Flashing</u>: Because of workpieces are initially clamped close enough (but not mechanical contact), high current can pass through one edge to the other forming electric arcs; here, an initial gap between workpieces edges can be defined as a variable: **Flashing gap** (g_F). This gap is regulated (independent from electric current magnitude or modulation) in order to control flashing; if g_F is too big there is no flashing because of current magnitude in not sufficient to beat disruptive electric resistance of air (or maybe some kind of isolation gas), but if g_F is too small arcs extinguish because mechanical contact between welding edges.

A correct g_F allows the formation of rapid outgoing sparks, result of arcing explosions removing material in form of sparks; commonly g_F regulates the amount of sparking, also called flashing. It is important to note that most FB welder machines works at pre-defined values for g_F (between two or four constant values), forcing to find another control variable for governing flashing. Optimal flashing process, with losing of mass in form of sparks (melted metal), heats the material and allows inclusions and impurities expulsion, also prepares good mechanical conditions for next stages.

High current and low voltage are applied on FB welding, these are provided by a high power transformation electromagnetic circuit. FB welding machine clamps are directly connected to the secondary coil as an open circuit; when g_F is small enough, arcing is produced closing the circuit. In this context: **Flashing current** (I_F) and **Flashing voltage** (V_F) can be defined as time independent variables; **Flashing resistance on gap** (R_F) complements I_F and V_F. **Flashing heat input** (E_F) and **Flashing time** (t_F) are defined as variables with both combined represents the amount of input energy on flashing. Because of different conditions of flashing when modulation of I_F may vary depending of the material, depending of the FB welding machine and other factors, the **Flashing coefficient** (η_F) is necessarily defined in order to measure the energetically stage effectiveness. Principally, η_F may depends of g_F and I_F and disturbs E_1.

Another important mathematical variable on flashing is **Flashing electrode feedspeed** (v_F), which represents the cooperative electrode velocity (towards the other electrode, for forging) in order to compensate mass losing, maintaining g_F constant (constant/controlled flashing). **Flashing electrode upsetting force** (F_F) complements v_F. It is important to note that upsetting variables are commonly pre-defined as constant values for most FB welding machines.

<u>Holding</u>: Flashing and holding stages are similar, most mathematical variables defined for flashing stage are analogue on holding: **Holding gap** (g_H), **Holding current** (I_H), **Holding voltage** (V_H), **Holding resistance** (R_H), **Holding heat input** (E_H), **Holding time** (t_H), and **Holding coefficient** (η_H). It is important to note that g_H is very small, practically

zero, ensuring mechanical contact between workpiece edges starting the welding interface (mathematically g_H can be considered with a negative sign, close to zero, because of the vector direction change, interpreted like a little pressing effect). Therefore, **Holding electrode feedspeed** (v_H) is practically zero because no electrode movement and **Holding electrode upsetting force** (F_H) is minimal, close to zero, ensuring the little pressing effect (like in g_H case).

It is important to note that holding stage could be present after or before pressing stage; the objective is to promote a successful microstructure. Holding stage is important to allow input welding energy heats a bigger zone on base metal without losing mass as in flashing; here flashing and sparking are not present. I_H needs to have the necessary magnitude to sustain a sufficient heating resistance for the virtual heat treatment; Joule´s law of heating resistance models E_H in a more representative way than modeling E_F; R_H is practically constant compared with R_F which is very unstable. Commonly t_H is shorter than t_F, in some cases t_H is too short that holding stage can be neglected.

Forging or Pressing: Mathematical variables on pressing stage are also analogue to flashing and holding stages. **Pressing gap** (g_P) uses a minus sign because of vector direction expressing an upsetting distance; maximum absolute value of g_P is d_P. **Pressing current** (I_P), **Pressing voltage** (V_P), **Pressing resistance** (R_P), **Pressing heat input** (E_P), **Pressing time** (t_P) and **Pressing coefficient** (η_P) are all related with electric energy input on pressing stage. Commonly I_P is different than in the other stages, on pressing stage I_P needs to maintain or decelerate cooling rate (In the case of holding stage sits after pressing stage, the sustaining current I_P turns into I_H; only nomenclature). On η_P is intended to estimate the plastic deformation effect on electric resistance. **Pressing electrode feedspeed** (v_P) and **Pressing electrode upsetting force** (F_P) are variables related to mechanical energy input on pressing stage; F_P on pressing stage is bigger than in the other stages because of the forging; but even mechanical energy is bigger than in other stages, it still small compared with electric energy input.

Positioning holding stage after or before pressing stage is going to be defined on future works; until that, both possibilities will be maintained in order to determine which promotes better results.

3.4. Post-welding

After FB welding, when base metals cools, is commonly to apply a focused normalizing heat treatment on welded region in order to reduce brittleness (specifically Martensite formation). Because of there are more than one way to apply the normalizing treatment after welding (using an oven, using a torch, or maybe using an electric method) the mathematical variable can be defined in terms of input energy. It is intended to converge post-welding treatment to use electric methods; this is economically and time consuming favorable, because of on practice the same FB welding machine can be configured to do this work. Consequently, **Post-welding heat input** (E_T) is defined for measure heat treatment energy; **Post-welding current** (I_T), **Post-welding voltage** (V_T), **Post-welding resistance** (R_T), **Post-welding coefficient** (η_T) and **Post-welding treatment time** (t_T) complement E_T. Because is a static process, there is no upsetting time, any gap, no pressing force and no feed speed.

It is important to note that post-welding treatment can be done just before welding or when welded regions are cooling down. This two possibilities are very different: In the first case E_T performs more like a cooling rate decelerator in order to void brittle formations (in this case, post-welding is the same of holding stage after pressing stage); on second case, E_T needs to heat workpiece again from room temperature and holding the heat until convenient growing-diffusion soft phases takes place. Present work focuses on the first method, applying heat treatment just after welding; in this case, if electric resistance independence of temperature is assumed, R_T is equal to R_P.

4. MATHEMATICAL MODEL APPROACH, AND DISCUSSIONS

The fact that some variables were defined previously do not means all mathematical variables to model FB welding are defined; in fact, into the mathematical model approach some other main variables will be in discussion. Next paragraphs show the relationship between mathematical variables and technical FB welding considerations.
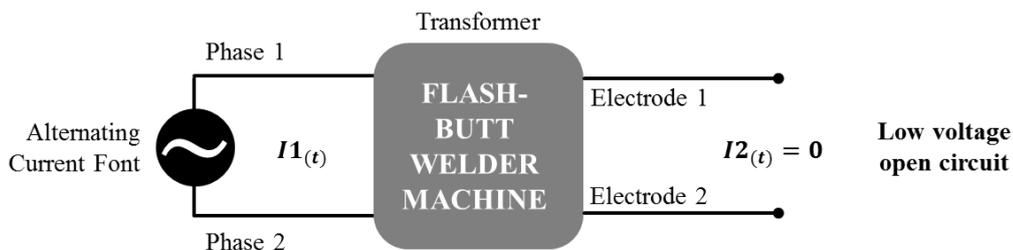

Figure 1: Disconnected Flash-Butt welder machine schematic

Figure 1 shows and electric simplified schematic of a FB welder machine, which technically performs like a high current transformer. An alternating current (AC) font provides energy to the electric power system of the machine (high

power flashing circuit), and normally it is not distributed to the pressing system or the control system components with have different energy sources. On flashing circuit two electrodes are directly connected to the secondary coil of the transformer; if there is no workpiece, a differential of potential can be measured from both electrodes, but there is any current available (open circuit).
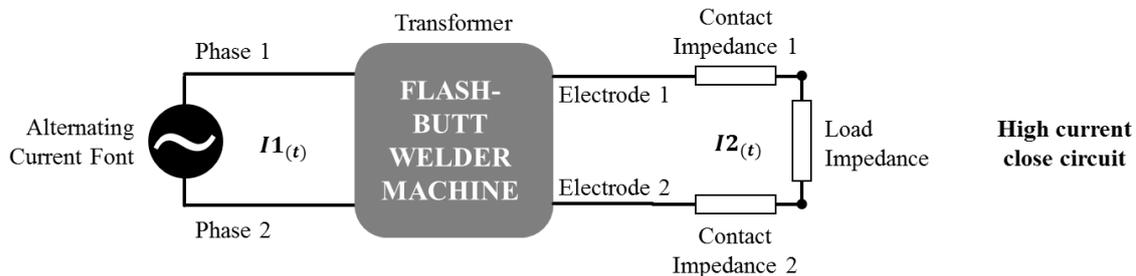

Figure 2: Connected Flash-Butt welder machine schematic

Figure 2 shows the same schematic presented on Fig. 1 but connected to the workpieces (sheet metal steel); the contact impedance 1 and 2 corresponds to the electrode-workpiece contact resistances R_{C1} and R_{C2} respectively. Load impedance represents the stage electric resistance on flashing, holding, pressing or post-welding; all of these are not the same, but depending of the FB welding stage one can be replace the other. Note that the term "impedance" it is not the same than "resistance", in order to clarify that a third hypothesis can be considered: *"Inductance and capacitance behavior can be neglected, because of the Resistive Power (active or real power) is much greater than Reactive Power; Power Factor (PF) can be assumed to be close to 1 ($\cos\varphi \sim 1$)(on practice $\cos\varphi \approx 0.8$)"*. This fact, for a first mathematical approach, actually simplifies the calculations avoiding the use of imaginary number and phasorial algebra. Another important reason to assume circuit impedances as simply resistances is that the phasorial angle delaying is not important, it is assumed that the whole network (in this case the high current circuit) works at the same font frequency (AC font, commonly: 50-60 [Hz]).

From previous Fig. 2, it is easy to note that effective or total resistance is the summation of two times R_C plus the workpiece resistance depending of the FB stage. On clamping stage (or open circuit mode) a very high resistance can be assumed, do not allowing any current to pass. When flashing, R_F takes place and it is strongly dependent of flashing conditions (very unstable). If internal thermo-electrical phenomena is ignored, the electrical workpiece resistance on holding stage, pressing and post-welding stages are the same ($R_H = R_P = R_T$); this feature needs more investigation.

Figure 3 (next page) shows where previous defined distances, separations and gaps are positioned. At the top of the figure, in the clamping stage, electrode clamping describes schematically how the workpiece is fastened; here workpiece can be any piece of metal, but this paper focuses on thin steel sheet welding (Fig. 3 shows cross section of the sheet). Note that it is assumed a general symmetry around the welding interface; on practice, one electrode is fixed and the other is mobile (cooperative), this fact do not disturb the symmetry assumption but simplifies the mathematical analysis. Electrode separations (also the gaps) are shown divided by two because of the symmetry.

Figure 4 (next page) expresses units conforming the International System convention. Because the governing equation presented next paragraphs, Temperature is the scalar variable defined as the monitoring dependent variable; temperature profile is key to determine phase transformations on steel thermo-mechanical processes. On Fig. 4 it is shown the maximum temperature profile at one central point on the symmetric welding interface. This representation apparently is simple, but it is important to note that it is describing the thermal behavior of only one point. A more complete representation (representing a material point behavior in space) needs a three dimensional graph; full representation is a graph with five dimensions, three for the graph and two for two independent grades of motion (x, and t), like sea waves.

Note that temperature curve on flashing stage is like an exponential kind curve; on holding stage temperature appears stay static (holding stage, after or before pressing stage, has a constant temperature profile), actual changes could not be represented in these graph (heat affected zone increases; it is well represented on a x axis perpendicular to T and t). On pressing stage temperature starts slowly going down, it is needed plastic deformation to occur. Post-welding (or maybe after pressing holding stage), slows down the cooling rate in order to allow excessive brittle formations like Martensite.

Voltage is assumed to be constant the whole process, as shown on Fig. 4, actually it has drops when applied curret vary; moreover, FB welding machines has voltage regulation control, in order to compense current undesired oscillations. If current performs like $I_{(RMS)}$ graph curve (on Fig. 4), and the voltage is constant, the active power behavior is like an escaled curve from $I_{(RMS)}$ curve. It can be undestood that the maximum active power is in pressing stage, holding and post-welding stages are similar, and flashing stage has the minor active power applied. These afirmations, need to be corroborated with data adquisition methods; this job is going to be developed on future works.

In the same context, effective electric resistances are calculated from the quotient of voltage and current; here resistance behavior shows some relation with temperature profile, it can be inferred that the higher the temperature the minor the resistance, wich it is contradictory to literature data (i.e. superconductors, and high impedance at high

temperatures). Constant voltage is not a representative assumption, it is dificult to confirm resistance relationship with temperature; this behaviour needs more investigation. Another important fact to discuss from Fig. 5 is that mechanical input energy is almost smaller than electric input energy; this is why varying upsetting force almost do not affect welding properties, as Chenyao et. al. (2016) had shown. The maximum mechanical energy input takes place on pressing stage.
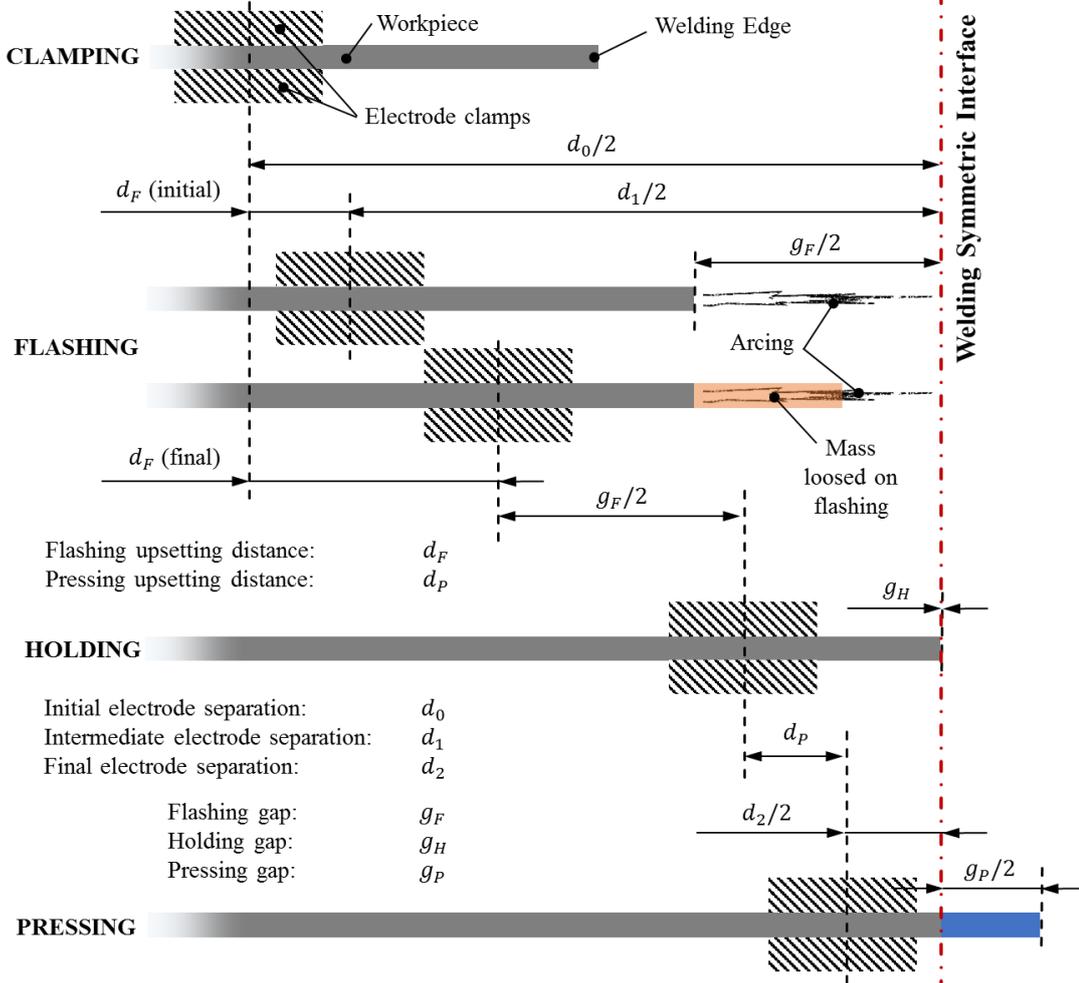

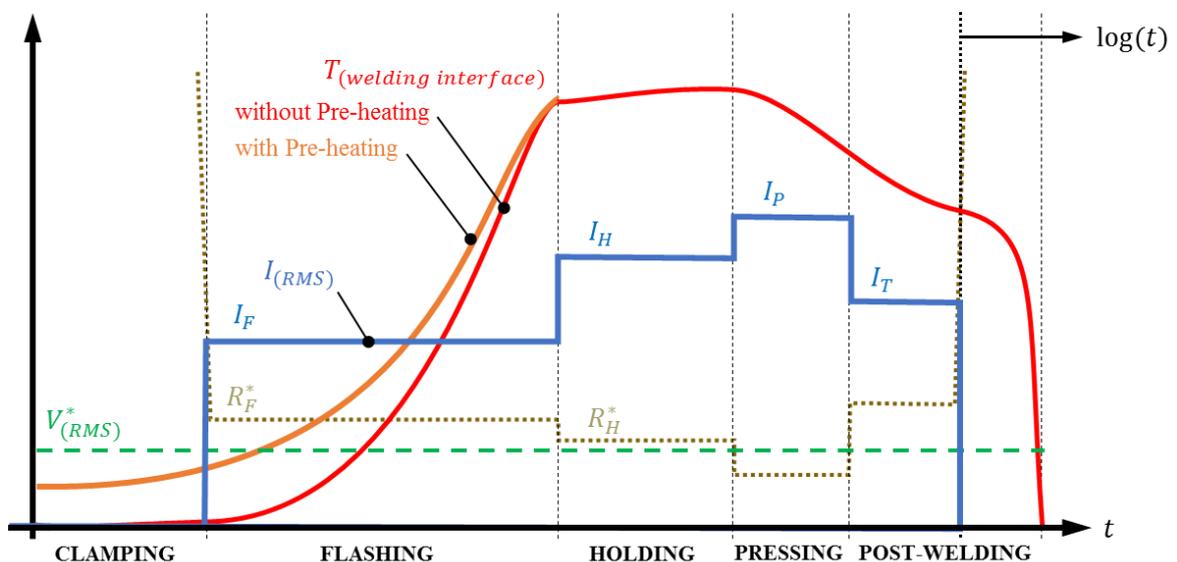**Figure 3: Flash-Butt welding stages diagram**

Figure 4: Variables behavior assumption on Flash-Butt welding process (not scaled)
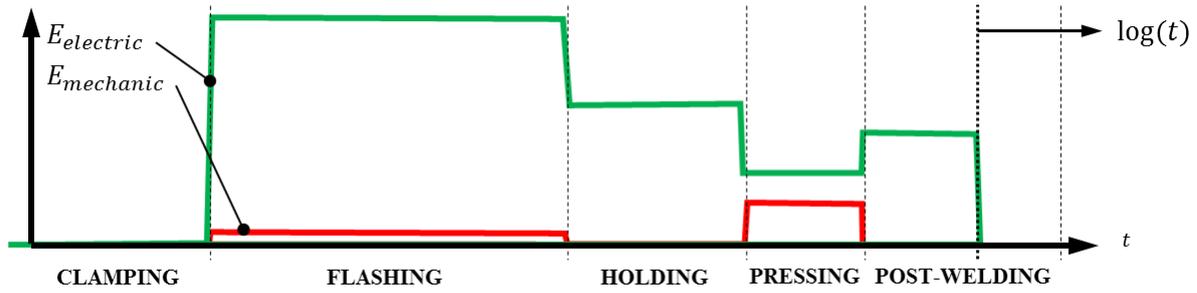
Figure 5: Mechanical energy input compared with electric energy input (not scaled)

For a first approach to mathematical modelling, previously defined variables were based on three hypothesis: 1.- Constant chemical composition (mass losing but maintaining proportions), 2.- Thermo-mechanical variables could be independent of time and position, and 3.- Inductance and capacitance behavior are neglected. Governing equation, derived from heat transfer principles, for a generic case could be defined as the following partial differential equation:

$$\rho c_p \frac{\partial T}{\partial t} - \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) = Q - L \qquad \text{Where: } T = T_{(\bar{x},t)} \qquad (1)$$

Note that the main variable is temperature, which can be defined as a function dependent of time and position; this governing equation models the behavior of temperature profile when cooling or heating. It is important to note that because the complexity of the problem, the solving process needs to focus the governing equation resolution into the stages or sub-processes; it is not possible to model the whole process with the same space and temporal conditions.

The forcing term, which vary on each stage, consists on **Net input energy** (Q) and **Heat losses** (L); these both, varying on time, act in different ways on each stages or sub-processes on FB welding. On consecutive studies, Q is going to be defined as function of the electrical (voltage and current on FB welding stages, including pre and post treatments) and mechanical (pressing force and speed on FB welding stages) inputs. Heat losses depend on convection and radiation losses (conduction are contemplated on the model) which for a first approach they can be neglected on heating procedures, but contemplated when cooling. Future works need to contemplate losses, especially radiation losses.

If **Thermal conductivity** (k), **heat capacity** (c_p) and **density** (ρ) are considered invariant on space and time, Eq. (1) simplifies. Problem can be considered as 1 spatial dimension problem if: Material is considered isotropic; the thickness of the sheet is small enough to dismiss changes on this axis; and infinite with of sheet in order to mount a representative material line. In this case, $T_{(\bar{x},t)}$ can be expressed by $T_{(x,t)}$; governing equation could be as follows:

$$\frac{\partial T_{(x,t)}}{\partial t} = E_0 \qquad \text{For: } \begin{array}{l} x \in [0,l] \\ t \in [0,t_0] \end{array} \qquad \text{Where: } E_0 \propto \frac{Q_0}{\rho c_p}, \text{ and: } \begin{Bmatrix} E_M = 0 \\ E_E \gg 0 \end{Bmatrix} \qquad (2)$$

$$\frac{\partial T_{(x,t)}}{\partial t} + \omega^2 \frac{\partial^2 T_{(x,t)}}{\partial x^2} = E_F - L \quad \text{For: } \begin{array}{l} x \in [0,\infty[\\ t \in [0,t_F] \end{array} \quad \text{Where: } \omega^2 = \frac{k}{\rho c_p}, E_F \propto \frac{Q_F}{\rho c_p}, L \approx L_{Rad}, \text{ and: } \begin{Bmatrix} E_M \approx 0 \\ E_E \gg E_M \end{Bmatrix} \qquad (3)$$

$$\frac{\partial T_{(x,t)}}{\partial t} + \omega^2 \frac{\partial^2 T_{(x,t)}}{\partial x^2} = E_H - L \quad \text{For: } \begin{array}{l} x \in [0,\infty[\\ t \in [0,t_H] \end{array} \quad \text{Where: } E_H \propto \frac{Q_H}{\rho c_p}, L \approx L_{Conv}, \text{ and: } \begin{Bmatrix} E_M = 0 \\ E_E \gg 0 \end{Bmatrix} \qquad (4)$$

$$\frac{\partial T_{(x,t)}}{\partial t} + \omega^2 \frac{\partial^2 T_{(x,t)}}{\partial x^2} = E_P - L \quad \text{For: } \begin{array}{l} x \in [0,\infty[\\ t \in [0,t_P] \end{array} \quad \text{Where: } E_P \propto \frac{Q_P}{\rho c_p}, L \approx L_{Conv}, \text{ and: } \begin{Bmatrix} E_M \gg 0 \\ E_E > E_M \end{Bmatrix} \qquad (5)$$

$$\frac{\partial T_{(x,t)}}{\partial t} + \omega^2 \frac{\partial^2 T_{(x,t)}}{\partial x^2} = E_T - L \quad \text{For: } \begin{array}{l} x \in [0,\infty[\\ t \in [0,t_T] \end{array} \quad \text{Where: } E_T \propto \frac{Q_T}{\rho c_p}, L = L_{Conv}, \text{ and: } \begin{Bmatrix} E_M = 0 \\ E_E > 0 \end{Bmatrix} \qquad (6)$$

Equations above are separated on FB welding stages or sub-processes; note the evolution of **Mechanical energy input** E_M and **Electrical energy input** E_M. **Thermal Diffusivity** ω^2 is squared only for simplifying purposes. Phase transformation it is not included on these equations, but knowing an accurate temperature profile evolution it is easier to predict microstructural changes. Note that pressing stage is going to be contemplated only as an extra input energy (influencing the temperature profile); in this case, a separate simulation is planned, in order to model the forging process.

5. CONCLUSION

Consecutive processes were defined in order to analyze behavior of FB welding variables; the objective is to define an accurate mathematical expression for each stage of the process. Next tables resume all variables mentioned paragraphs above, a classification between general and process variables is done:

Table 1: General and Process variables

GENERAL VARIABLES	SYMBOL	PROCESS VARIABLES	SYMBOL
Carbon content	$C\%$	**Initial electrode separation**	d_0
Equivalent carbon content	$CE\%$	**Intermediate electrode separation**	d_1
Thermal conductivity	k	**Final electrode separation**	d_2
Specific heat	c_p	**Flashing upsetting distance**	d_F
Density	ρ	**Pressing upsetting distance**	d_P
Pre-heating input	E_0	**Temperature profile**	$T_{(0,t)}$
Electrode-workpiece contact resistance	R_c	**Temperature distribution**	$T_{(x)}$

Table 2: Welding zone variables

	Initial (BM)	HAZ	FZ	HT HAZ	HT FZ
Martensite Volume Fraction	$M_i\%$	$M_{HAZ}\%$	$M_{FZ}\%$	$M_{HT\,HAZ}\%$	$M_{HT\,FZ}\%$
Yield Strength	σ_{Y_i}	σ_{Y_w}		σ_{Y_f}	
Ultimate Strength	σ_{U_i}	σ_{U_w}		σ_{U_f}	
Hardness (Brinelli scale)	HB_i	HB_{HAZ}	HB_{FZ}	$HB_{HT\,HAZ}$	$HB_{HT\,FZ}$

Table 3: Welding process stage variables

	FLASHING	HOLDING	PRESSING	POST-WELDING
Gap	g_F	g_H	g_P	g_T
Current	I_F	I_H	I_P	I_T
Voltage	V_F	V_H	V_P	V_T
Resistance	R_F (on gap)	R_H	R_P	R_T
Heat input	E_F	E_H	E_P	E_T
Time	t_F	t_H	t_P	t_T
Coefficient	η_F	η_H	η_P	η_T
Electrode feed speed	$v_F > 0$	$v_H \approx 0$	$v_P > 0$	$v_T = 0$
Electrode upsetting force	$F_F > 0$	$F_H \approx 0$	$F_P \gg 0$	$F_T = 0$

It is proposed to use a Specific Purpose Informatic Solver (SPIS) because the complexity of the solution; some analytical solutions (like a prediction mode) can be inferred using Laplace Transformations or Fourier Decomposition. However, before using any solver/informatic code, it is necessary to develop some kind of classification of variables in order to obtain the variables hierarchy. This previous step simplifies the problem, and marks useful variable relations.

Problem is simplified to describe the thermal profile evolution (heating and cooling) on a material line (1D) varying on space (x) and time (t); once it behavior is well established, next procedure is to apply this thermal behavior to predict microstructure evolutions, caused by phase transformations. Basically, the algorithm is to run different thermal behaviors to produce different changes on microstructure (focused on welded regions), until to find a prediction of the best method. Here, a meticulous tuning of variables and parameters is needed; informatic and mathematic resources are key. Microstructure predictions are easy to link with mechanical behaviors.

Actual model cannot be enough sensible or predictable to describe pressing stage issues. For this reason, a separate modelling is needed. A Finite Element Method (FEM) is recommended to model the plastic deformation on pressing stage; this FEM would need some temperature as input data, actual model can predicts this information.

On future works, a well understanding of the next topics is needed:

- The influence of Martensite morphology on welding cracks (influence of volume fraction of Martensite is already known). This study can suggest some necessary adjustments to the presented model.
- Temperature influence on steel impedance magnitude needs more investigation (thermo-electric variables).

- Electric variables behavior on-process also needs more research (Power factor variations, phasorial changes on impedances, modulation of electric current, voltage compensation, etc.)
- The proportion between input energy and heat generated need to be well understood.

As a formal recommendation: More research it is needed to validate presented equations and associated variables, corroborating information with Data Adquisition Methods (DAM); this job is going to be developed on future works.

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