A translational coupled electromagnetic and thermal innovative model for induction welding of tubes

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Abstract — In the paper, a novel approach to numerical modeling of tube welding is proposed. The coupled electromagnetic and thermal model must take into account also the movement of the metal strip: in order to make possible this kind of simulation in reasonable computation time, a simplified approach to the modeling is presented and discussed.

I. Introduction

The welding of tubes and pipes is usually achieved by high frequency induction heating. In recent years, solid state generators became available with rated power useful for this application, typically in the range 50 – 2000 kW, displacing the traditional vacuum tube oscillators. The solid state technology allows the possibility to choose the best frequency for the application, usually in the range 100 – 500 kHz. The better control of solid state inverters made the optimal design of welders crucial for the manufacturer [1]-[5].

Numerical modeling of induction welding process is required to achieve the best performance but this kind of simulation can be very complicated because the coupled electromagnetic and thermal solution has to take into account also the movement of the tube in a full 3D geometry.

In order to limit the complexity of the model, some simplifications are discussed and validated through simulations.

II. Computation model

The sketch of Fig.1 (a) shows a simplified geometry of the tube welding systems. When the bended strip approaches to the welding point, W, it has a “V” shape, usually named VEE. During the welding process the tube moves forward with a velocity, v_d, maintaining the welding point, W, at a fixed position with reference to the inductor. The solution of coupled magnetic and thermal problem is very difficult to be implemented because the shape of the load does not change during the translation.

The first simplification is related to the geometry of the tube: the VEE has a square shape as sketched in Fig. 1 (b) instead of the real geometry shown in Fig. 1 (a).

The thermal problem requires the computation of the power induced on the metal by the evaluation of the induced current density, Maxwell equations are solved in terms of magnetic vector potential, $\boldsymbol{A}$, and electric scalar potential, V [6]-[9].

Since eddy currents are concentrated close to welding edges and in the VEE zone, only the part of tube close to the inductor is considered in the simulation.

In the conductive region of the tube, Ω_T and Ω_W, the non-homogeneous Helmholtz equation is solved in time harmonic domain (Fig. 1 (b)):

$$\nabla^2 \dot{\boldsymbol{A}} + k^2 \dot{\boldsymbol{A}} = -\mu \dot{\boldsymbol{J}}\ , \quad k^2 = -j\omega\mu\sigma \tag{1}$$

where μ and σ are, respectively, the magnetic permeability and the electric conductivity of the materials. The Lorentz gauge has been imposed [6], [7].

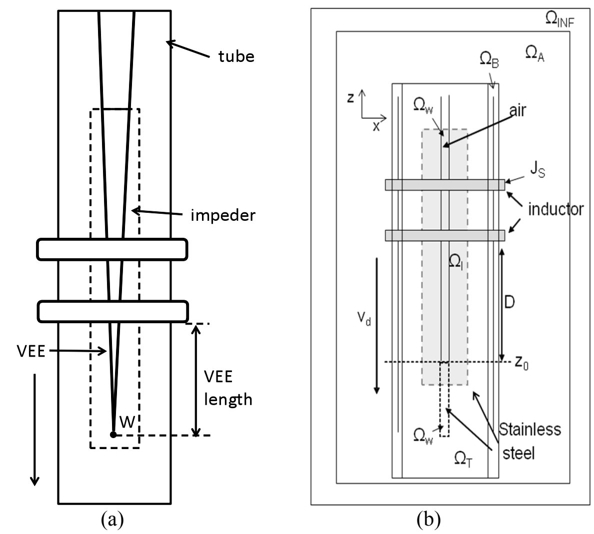

Fig. 1. (a) Geometry of the tube and (b) regions in the computation domain.

The second simplification proposed is related to the description of the tube movement in order to keep the welding point W fixed with respect to the inductor.

The region Ω_W is the welding region where the electrical conductivity, thermal conductivity and specific heat are described as a function of the *z* coordinate. We can use the unitary step function *u(z)*:

$$u(z) = \begin{cases} 0, & z < 0 \\ 1, & z \geq 0 \end{cases} \tag{2}$$

z=0 is the position of the welding point. If we want to describe the conductivity, σ, in the welding Ω_W region we can apply the *u(z)* function in such a way:

$$\sigma(z) = \sigma_A u(z) + \sigma_M (1 - u(z)) \tag{3}$$

where σ_A is a very low fictitious value of electrical conductivity used to describe a non conductive medium (10^{-6} S/m) and σ_M is the real conductivity of the metal (0.7-1.4 10^8 S/m). Similarly equations as (3) can be written for the thermal conductivity and specific heat. Considering a non magnetic steel for the tube material the relative magnetic permeability is unitary. With this approach, the

welding point is kept at the same position while the tube moves inside the inductor.
In the tube the conductivity varies with the temperature.

The current density $\dot{J}$ is computed in the tube region Ω_T, modelled as a conductive region, from the magnetic vector potential and the electric scalar potential by means of:

$$\dot{\boldsymbol{J}} = \sigma\dot{\boldsymbol{E}} = -\sigma(j\omega\dot{\boldsymbol{A}}) \qquad (4)$$

Where $\boldsymbol{E}$ is the phasor of the electric field.

In the air regions, Ω_A and Ω_B, not conductive, the coefficient k^2 in the (1) is null and the electromagnetic (EM) problem is solved only in terms of vector potential. The Ω_B region is a volume used for the translation of the tube and the mesh is constituted by tetrahedral elements built in such a way to simulate the movement in a proper way. In this case eq. (1) is reduced to a Poisson equation. The magnetic field source is an inductor constituted by two turns with an impressed current *I*. At the domain boundary region, Ω_{INF}, the magnetic vector potential is imposed to zero at infinite distance. In the impeder, a magnetic region inside the tube, eq. (1) is solved imposing both the material conductivity, σ, and the current source, $\boldsymbol{J}$, equal to zero and a Laplace equation is solved.

The temperature *T* on the tube region Ω_T and Ω_W , the thermal domain, can be evaluated solving the Fourier equation [10]:

$$c\gamma\frac{\partial T}{\partial t} = \lambda\nabla^2 T + p \qquad (5)$$

where the power density *p* is computed from the previous electromagnetic solution, λ is the thermal conductivity [$W\cdot m^{-1}K^{-1}$], *c* is the specific heat [$J\cdot kg^{-1}K^{-1}$] and γ is the mass density of the material [$kg\cdot m^{-3}$].

In this case the tube is supposed to be at room temperature at the beginning of the welding process (T = 293.15 K). Convection and radiation losses are considered for both inner and outer tube surface, as well as the welding edges. The outer temperature has been considered at 293.15K.

The simulation process has been implemented in a commercial Finite Element code [11].

III. Results

At the beginning a magnetic simulation is analyzed in order to evaluate the effect of the VEE shape on the current density distribution on the welding edges. In Fig. 2 the shape of the welding VEE used in the simulation is reported. The gray line is the side in which the current density in Fig. 3 has been evaluated. In Fig. 2 (a) is reported the shape of the real VEE, whereas in Fig. 2 (b) the simplified one.

In order to test the error made approximating the welding fissure, the current density on the tube edge has been evaluated and compared for the two types of VEE. In Fig. 3 the current density has been reported as a function of the spatial coordinate along the VEE edge. The current density on the approximated VEE has been evaluated varying the distance *a* between VEE edges between 0.5mm and 3 mm. In the real VEE (Fig. 2(a)) the *a* distance is close to 1 mm. The current density in the approximate VEE is close to the one of the approximated VEE with the *a* distance of 1 mm.

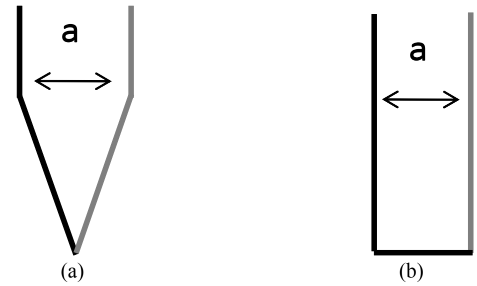

Fig. 2. Shape of the tube welding fissure, VEE. (a) real and (b) approximated VEE.

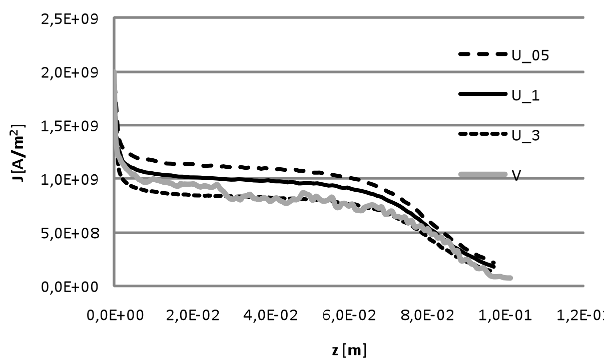

Fig. 3. Current density in the side of the VEE. Gray line real VEE in Fig. (a) and black lines in the approximated VEE.

IV. References

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