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APPLICATION OF COMSOL SOFTWARE TO SIMULATE INDUCTION HEATING PROCESS OF THE SEMISOLID STATE OF A356 ALUMINUM ALLOY IN THIXOFORMING PROCESSES

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ABSTRACT

Thixoforming techniques require metal alloys to be cast when they are partially liquid and partially solid. Before a material flows into a die cavity under pressure, the temperature distribution must be uniform within the billet at the end of heating in order to obtain a good microstructure. In this study, we use theoretical heat transfer and numerical methods in combination with COMSOL simulation to develop practical strategies aimed at saving the cross-examination time of the calculation process by numerical methods. This will form the basis for technology development at the industrial level and create the basic premises for further studies of applications of induction heating in general and thixoforming techniques in particular.

KEYWORDS: Thixoforming technique, induction heating, numerical method.

INTRODUCTION

Since the beginning of this century, a new casting technique called semi-solid metal (SSM) forming has become increasingly important in the forming of metal alloys. It was originally developed by Prof. Merton C. Flemings at the Massachusetts Institute of Technology in the 1970s and has since been commercialized and employed in industry. Compared with traditional methods of casting during the full liquid stage, the SSM technique requires metal alloys to be cast when they are partially liquid and partially solid, providing a higher flow viscosity during the casting process and therefore a higher quality of cast products by preventing the entrapment of gasses. Advantages of SSM include products with excellent surface quality, high strength, low levels of porosity, and fine microstructure, as well as energy savings during heating and formation processes and respect for tight tolerances [1-5].

Several metal alloys such as copper, magnesium, nickel, and ductile iron have been used for SSM casting, but aluminum alloys are more applicable to commercial manufacturing. For aluminum alloys, a 50% liquid fraction has been found to be a typical optimum. Figure 1 shows the semi-solid state of an aluminum specimen.

There are two technical directions of SSM forming: rheoforming and thixoforming. The rheoforming method makes castings from a liquid to a semi-liquid state; the forming technique usually requires the reheating of pre-processed feedstock with a fine structure up to a typical liquid fraction of 40%–50%. The thixoforming process incorporates four operations as: firstly, a bar of thixoformable raw material is cut into appropriate slug lengths. Then the slugs are heated in a controlled manner, using either an induction coil or a muffle furnace, into a uniform 'mushy' state. The heated slug is transferred to the shot sleeve of a suitably modified die casting machine and injected into a die. The component feeder and gating systems are then removed using a clipping press or band saw.

At such liquid fractions, the properties of the semi-solid alloys are very sensitive to variations in the liquid phase. Thus, the heating process must be accurately controlled to achieve a uniform temperature distribution in a material and in turn in the liquid fraction. Conversely, the heating process is required to be relatively rapid to maintain the initial globular microstructure; otherwise, the semi-solid alloys will not be able to fill the die cavity properly [6-7]. Therefore, research is required to suggest reasonable heating strategies. One area of research that would serve as a valuable support tool for feasibility studies would be to find a way to combine the method of calculating the heating process with the method of cross-examination by COMSOL software simulation, which is popularly used by researchers.

In induction heating, the maximum value of the current density is found at the surface. The current density then decreases rapidly from the surface to the center. This phenomenon is called the skin effect. Because of the skin effect, most of the power density (heat source) is concentrated on the surface. The outside will then heat more quickly than the inside. About 86% of heat is produced in the layer along the surface called the penetration depth, which decreases as the frequency is increased. To maximize electrical efficiency and minimize electromagnetic forces, commercial machines often operate at frequencies above 20 KHz. Such high frequency also allows a more compact system.

Determine the time variations of the heat source within a metal to achieve a temperature as close as possible to the target, when all boundary conditions are known. Find an optimal boundary cooling process to obtain the expected temperature distribution of the semi-solid material at the final time, provided that the heat source is known. We used a numerical method for calculation. The advantage of this method is that the mathematical analysis used to work out the process was very rigorous. The physical and logical concepts were clear, and the result was expressed as a function so as to clearly show the effect of factors on the distribution of temperature field [8].

The advantage of numerical methods is that they can solve heat transfer problems that other methods cannot. Moreover, depending on the capacity of the computers used, the calculation speed will increase the scope and scale of applications of numerical methods; the speed and accuracy of computers are such that numerical modeling has become an effective method for solving complex problems of heat conduction in engineering.

To solve the problem of heat transfer, we used the finite difference method with approximate temperature values at the nodes of sub-elements of space and time to simulate the continuous temperature distribution in physical reality. The function result of the temperature distribution was continuously transformed into the result of temperature values at the nodes. In this manner, the problem of solving the differential equations of thermal conductivity was converted into a problem of solving a system of mathematical equations at the nodes of the elements. Thus, we discretized the considered problem, established algebraic temperature equations of the elements, and solved them.

PHYSICAL NUMERICAL SIMULATION OF THE INDUCTION HEATING PROCESS

The basic components of an induction heating system include an AC power supply, induction coils (single or multiple), and a workpiece (material to be heated or treated), as shown in Figure 1. The power supply sends alternating current through the coil, generating a magnetic field. When the workpiece is placed in the coil, the magnetic field induces a current in it. According to Joule’s law, the induced current may generate heat without any physical contact between the coil and workpiece.

A cylindrical billet of aluminum alloy (A356) with radius R is vertically placed in an induction coil unit. The power supply generates an alternating current. An internal heating source is thus generated by induction. {1.2 [EN] Meaning unclear. Please clarify} To obtain uniform liquid fraction and good viscosity, the billet temperature should be kept within 575°C–580°C at the end of the heating process. The chemical composition of the A356 aluminum alloy used in this experiment is given in Table 1 and physical properties are given in Table 2. The temperature that the billet needed to reach the semi-liquid state, $f_s = 50\%$, is 583°C–585°C.

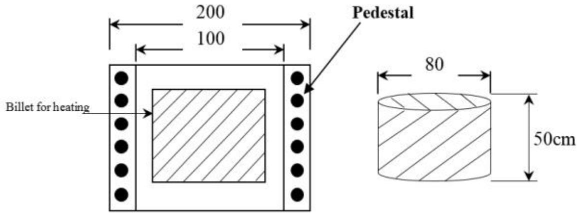

Figure 1: Model of induction heating coil for thixoforming

Table 1: Chemical composition of the A356 aluminum alloy

Si	Fe	Cu	Mn	Mg	Zn	Ti
6,59	0,01	0,12	0,005	0,39	0,005	0,005

Table 2: Physical properties of A356 aluminum alloy

Liquid temperature (°C)	615
Solid temperature (°C)	555
Specific heat (J/kg°C)	0,454.T (°C) + 904,6
Thermal conductivity (W/m °C)	0,04.T (°C) + 153,1
Density (kg/m^3)	−0,208T (°C) + 2680

The mathematical modeling of heat induction described in this study required 3 steps:

- Obtaining the heat transfer equation.
- Applying boundary conditions . These are a combination of heat transfer equation, the convection heat transfer equation, and the thermal radiation equation.
- Setting initial conditions.

The heating process was governed by the equation as follows:

$$\frac{1}{r}.\frac{\partial}{\partial r}.\left(k(T).r.\frac{\partial T}{\partial r}\right)+\frac{1}{r^2}.\frac{\partial}{\partial \theta}.\left(k(T).\frac{\partial T}{\partial \theta}\right)+\frac{\partial}{\partial z}.\left(k(T).\frac{\partial T}{\partial z}\right)+Q_{internal}=\rho(T).C_p.\frac{\partial T}{\partial t}$$

Or:

$$\frac{1}{r}.\frac{\partial}{\partial r}.\left(k(T).r.\frac{\partial T}{\partial r}\right)+\frac{\partial}{\partial z}.\left(k(T).r.\frac{\partial T}{\partial z}\right)+Q_{internal}=\rho(T).C_p(T).\frac{\partial T}{\partial t}$$

With

- $Q_{internal}$: denotes the internal source [W/m^3]

$$Q_{internal} = G(t) \times e^{-2.(R-r)/\delta}$$

$$\delta = 503.3.\sqrt{\frac{\chi}{\mu.f}}$$

○ The boundary conditions were given by

- r = 0: $k\frac{\partial T}{\partial r} = 0$
- r =R: $k\frac{\partial T}{\partial r} = q_{radiative\ heat\ flux,1} + q_{convective\ heat\ flux}(t)$

➢ $q_{radiative\ heat\ flux,1}$ = 5,67x10^{-8} x 0,05x [(T$_s$+273)^4 + (T$_{environment}$ + 273)^4], [W/m^2]

➢ $q_{convective\ heat\ flux}$ (t): heat strategy need to calculate in every heating time, [W/m^2]

○ The initial conditions were given by

- z = 0: $k\frac{\partial T}{\partial z} = 0$
- z = H: $k\frac{\partial T}{\partial z} = q_{convective\ heat\ flux} + q_{convective\ heat\ fluxạ,2}$

We performed the optimization for both heating and cooling problems through the determination of G (t) and q (t). Both functions need to satisfy the conditions as follows:

$$q(t) \le 0,$$
$$G(t) > 0.$$

The CGM {} algorithm may be summarized as follows:

- Make an initial estimate G0 = G0(t), q0 = q0(t), n = 0
- Solve the direct problem with Gn và qn to find Tn
- Solve the asymptotic problem to find Lagrange value $\lambda(x, y, z, t)$
- Replace the value $\lambda(x, y, z, t)$ on Gradient of error function in the direction of G và q
- Evaluate the difference, Tk(x, tf)–TE
- Calculate the search direction P1n và P2n using the equations as follows:

$$P_1^n = -J'_n[G(t)] + \gamma_1^n.P_1^{n-1} \quad (2)$$

$$P_2^n = -j'_n[g(t)] + \gamma_2^n.P_2^{n-1},$$

- $\gamma^n = \frac{\int_0^{t_f}[J'_n(t)]^2dt}{\int_0^{t_f}[J'_{n-1}(t)]^2dt}.$
- Update the guess value to Gn+1(t) và qn+1(t) as follows:
- $G^{n+1}(t) = G^n(t) + \beta^n P^n(t),$
- $q^{n+1}(t) = q^n(t) + \beta^n P^n(t).$
- Set n = n +1; go back to step 2 and repeat until the convergence criterion J^n < ε is satisfied

RESULTS AND DISCUSSION

During the process of optimizing the induction heating using the CGM algorithm, to solve the heat transfer equation, we had to combine the finite difference method according to the steps as follows:

- Based on the geometry and physical properties of the actual thermal conductivity problem, find a logical way to analyze and simplify the physical model such that it is still consistenting with the fact.
- Based on the physical model, setup a complete mathematical model consisting of the differential equations of conduction and boundary conditions.
- Discretize space and time for the heat conduction problem that is being considered, such that finite elements with certain requirements can be obtained. Use the temperature at the center of each node to represent the temperature of the discrete elements.

- Establish a system of algebraic equations at the nodes.
- Solve the temperature algebraic equations at the nodes, thus finding their heat value.
- Analyze the obtained results.

To perform quick and accurate calculations, calculate the loop with the CGM method and solve the heat transfer problem using Matlab software with the results as follows:

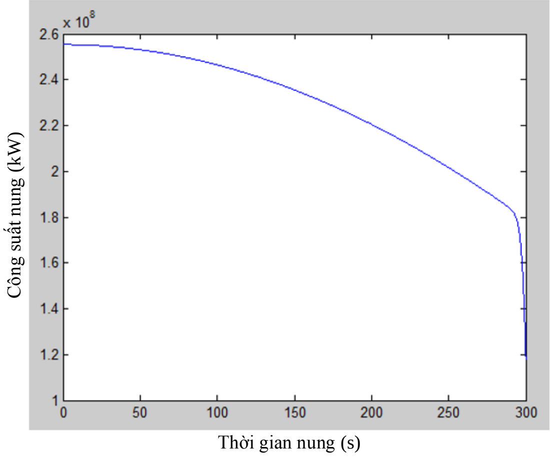

Figure 2: Optimal heating strategy by CGM

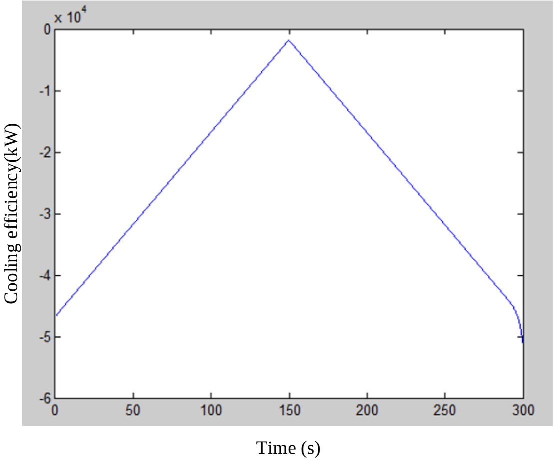

Figure 3: Optimal cooling strategy by CGM

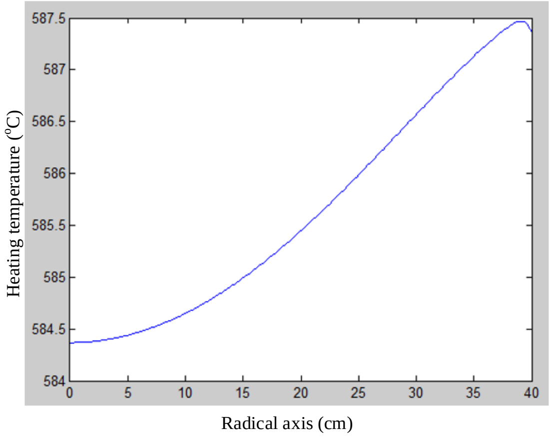

Figure 4: Surface to core temperature profile.

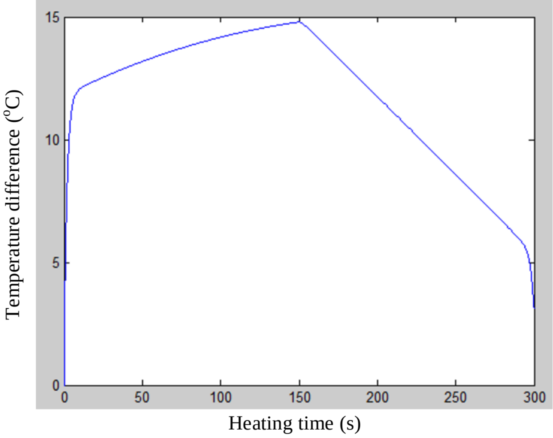

Figure 5: Temperature difference vs. heating time.

As shown in Figures 2–5, the aluminum alloy heating process to the semi-liquid state was found to have two main stages as follows:

- Phase 1 (0–150 seconds). During this phase, the heated billet is increased temperature according to parabola (Figure 2); concurrently, with this process, we also make the surface cooled of the part in a straight linear (Figure 3) with lessen intensity. Because of surface effects, the center temperature was higher than the surface temperature. However, the temperature of the heated billets still increased regularly. During this time, the cooling process still had to be maintained because the temperature difference inside the billet was still increasing and was larger than 10°C.
- Phase 2: the heated billet still increased in temperature according to a quadratic function (Figure 2) with the cooling incorporation at the same time, However, Figure 3.3 shows that heat during this period

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changed and decreased tendentoiusly. During this period, the temperature inside the billet became more evenly distributed, and the temperature difference decreased more until about 200 seconds, at which time, the temperature difference was less than 10°C (Figure 5). After 300 seconds, the surface temperature reached 587.3°C, whereas the center temperature reached 584.1°C.

CONCLUSION

In thixoforming techniques, the temperature control of the entire volume of a billet is very important and crucial to the quality of castings. Therefore, a combination of calculation and numerical simulation using COMSOL is required to find a feasible method to determine the reasonableness of the theoretical basis in simulations of induction heating processes of the A356 aluminum alloy in the semisolid state. In this study, the results of COMSOL simulation and a numerical method help us to assess their accuracy and reliability. Our model constitutes the basis for rapid experimental development and yields our desired results. COMSOL software can help researchers in the field of material shape, because it can be applied as a tool for the numerical simulation of heat flow exchange and diffusion.

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