Improving the energy efficiency by process parameter optimization approach: a case study for induction heating

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Abstract: This paper introduces a method of improving the energy efficiency using process parameter optimization approach. The energy consumption of a manufacturing process depends not only on the efficiency of its machines and equipment but also the process parameter. An optimum process parameter can increase the energy efficiency effectively. A case study for induction heating process is demonstrated to show the application of process parameter optimization approach. The result shows that the energy efficiency can varies 10% in the valid input range of process parameter. Therefore, the selection of optimum process parameter is the best way, which is low or zero capital cost, for improving the energy efficiency

Keywords: Energy savings, Induction Heating, Process Parameter Optimization

1. Introduction
Energy-saving manufacturing is receiving considerable attention from manufactures due to environmental legislation, cost-saving pressure, and competition [1]. Improving the energy efficiency is a promising solution for sustainable development [2, 3]. The heating process prior to hot forging mechanical parts, making combustion engine crankshafts for example, consumes a great amount of electrical energy when heating workpiece from ambient temperature to high temperature. Therefore, the increase in energy efficiency is significant. Diverse published works have been devoted to optimizing induction heating [4-9], but most of them focused on how to minimize temperature deviation at the end of the heating process. These published works have not focused intensively on minimizing the energy consumption the heating processes. In addition, induction heaters manufacturers are paying great attention to find ways of maximizing the energy efficiency of their equipment, such as improving the power supply, induction coils, and sophisticated refractory [4]. Although induction heating has been studied intensely, a method that optimizes the process parameters the heating in terms of energy efficiency and heating quality still needs to be developed systematically. Optimization of the process parameter is a solution which is low cost and easier to implement because it does not require any special devices or equipment investment. This paper presents the methodology of optimization of induction heating process parameter in terms of energy efficiency.

2. Mathematical and numerical modeling of the induction heating process
Induction heating process is considered as a high productivity, repeatable quality, and green heating technology compared to fuel-fired furnaces. This is the reason why induction heating is preferred in forging industry. The layout of an induction heating system consists of a power supply that converts electrical energy of line frequency (50/60 Hz) into well-controlled power of higher frequency, a matching circuit (or heat station) containing capacitors and a matching transformer that receives the output current from the power supply, induction coil(s), and a control system (Figure 1). An actual induction heating system is demonstrated in Figure 2.

![Fig. 1 Layout of induction heating system](image1)

![Fig. 2 An induction heating line of a long steel bar prior to hot forging](image2)

Induction heating is a complex electromagnetic and heat transfer process because of the temperature dependency of the electromagnetic, electrical, and thermal properties of material. The mathematical and numerical modeling of the electromagnetic field is governed by Maxwell’s equations and heat transfer equations. Following is a brief description of the
main governing equations and the structure of the coupling electromagnetic and thermal analysis.

\[ \nabla \times E = -\frac{\partial B}{\partial t} \quad \text{(Faraday’s law)} \quad (1) \\
\nabla \times H = J + \frac{\partial D}{\partial t} \quad \text{(Ampere’s law)} \quad (2) \\
\nabla B = 0 \quad \text{(Gauss’s law)} \quad (3) \\
\nabla D = \rho \quad \text{(Gauss’s law)} \quad (4) \\
\]

where \( E \) and \( H \) are the electric field intensity and magnetic field intensity, respectively; \( B \) and \( D \) are the magnetic flux density and electric flux density, respectively; \( J \) is the current density, \( \rho \) is the electric discharge, \( \nabla \times \) and \( \nabla \) denote the curl operator and divergence operator respectively.

The system of Maxwell’s equations is couple with following constitutive relations:

\[ D = \varepsilon E \quad (5) \]
\[ B = \mu H \quad (6) \]
\[ J = \sigma E \quad (\text{Ohm’s law}) \quad (7) \]

where \( \varepsilon \) is the dielectric constant, \( \mu \) and \( \sigma \) are magnetic permeability and electrical conductivity, respectively.

The Joule heat is calculated as

\[ Q_{\text{ind}} = E \cdot J = J / \sigma \quad (8) \]

Heat conduction for elements inside the workpiece

\[ \rho c_p \frac{\partial T}{\partial t} = k \nabla^2 T + Q_{\text{ind}} \quad (9) \]

Heat conduction for elements outside the workpiece

\[ \rho c_p \frac{\partial T}{\partial t} = k \nabla^2 T + Q_{\text{env}} \]

Due to the complexity of the electromagnetic and heat transfer processes, the exact analytical method is difficult to implement. Thus, a general-purpose FEM (Ansys software) was employed to analyze and simulate the induction heating process. Figure 3 shows the structure of the coupling electromagnetic and thermal analysis.

3. Energy Efficiency Analysis

This work aims to improve the energy efficiency of the induction heating system based on the simulation approach. Figure 4 shows the energy flow in the induction heating process. The energy losses comprise of convection and radiation losses, heat losses caused by conduction, heat transfer to cooling system, and the electromagnetic losses. The energy efficiency is defined as

\[ \eta = \frac{W_{\text{th}}}{W_{\text{el}}} \quad (11) \]

where \( W_{\text{th}} \) and \( W_{\text{el}} \) are the thermal energy stored in the workpiece and the electrical energy input to the coils (inductors), respectively.

The heat stored in the workpiece is calculated as

\[ W_{\text{th}} = \sum_{i=1}^{n} \Delta H_i V_i \quad (12) \]

where \( \Delta H_i \) and \( V_i \) are the enthalpy and the volume of the \( i^{th} \) element, respectively.

The electrical energy is evaluated as the product of the real part of the current and voltage in the inductor. These values are obtained in the numerical analysis. Because the Joule heat and heat losses of the induction heating depend on the temperature range, the energy efficiency is evaluated for each heater, as well as for the total energy efficiency of the heating line.

The temperature deviation \( \sigma \) is defined as

\[ \sigma = \frac{\sum_{i=1}^{n} (t_i - t_{\text{avg}}) V_i}{V} \quad (13) \]
where the average temperature of the workpiece is calculated as

\[ t_{avg} = \frac{\sum t_i V_i}{V} \]  \hspace{1cm} (14)

\( t_i \) and \( V_i \) are the temperature and volume of the \( i^{th} \) element, respectively; \( V \) is the volume of the workpiece; and \( n \) is the number of elements.

4. Process Parameter Optimization

In this paper, we demonstrate a case study for optimization of the process parameter of an in-line induction heating prior to hot forging of an automotive crankshaft (Figure 2 and 5). There are seven heaters in the heating line which are divided into three groups fed by three independent power supplies due to flexible control. There are three process parameters: voltage \( V \), frequency \( f_1 \), and frequency \( f_2 \). The frequency \( f_2 \) is adjusted to obtain the target temperature. The concerned outputs are average temperature, temperature deviation, power consumption, and energy efficiency. We not only consider the energy efficiency but also ensure a heating quality. The multi-optimization problem is stated as follows:

- Maximize the energy efficiency \( \eta \)
- Minimize the temperature deviation \( \sigma \)

Subject to constraints:

\[ 700 \leq f_1 \leq 1100; \]
\[ 900 \leq f_2 \leq 1300; \]
\[ 450 \leq U \leq 550. \]

To solve the above optimization problem, metamodel based optimization method was applied (Figure 6). The design of the experimental method was adopted to organize the combination of design parameters. We used the second order response surface methodology (RSM) as a metamodel due to the moderate nonlinear behavior of the induction heating process. A full factorial design matrix was applied for parameter studies. The value of each parameter (factor) is divided into three levels, so there are \( 3^3 = 27 \) experiments. Initial and final temperatures of the workpiece are 25°C and 1220°C, respectively. The billet moves at a speed of 460 mm per 25 seconds. The length of each heater is 1000 mm, and the distance between adjacent heaters is 300 mm.

Figure 6 shows the systematic procedure for optimizing the heating process parameters and the algorithm of metamodel-based optimization. After performing simulations, the data was used to generate the RSM model (meta-model). The fidelity of the approximate model is then verified. If the meta-model is accurate enough, the optimization process is carried out based on this model. Solving the optimization based on the metamodels yields the optimum process parameters which maximize the energy efficiency.

The multi-objective optimization problem was solved by a non-dominated sorting genetic algorithm (NSGA2). The parameters of NSGA2 are as follows: population size, number of generation, crossover probability, crossover distribution index, and mutation distribution index, and their values were 20, 40, 0.9, 20, and 100, respectively. Because the energy efficiency is more important than temperature deviation, the weights for energy efficiency and temperature deviation were selected as 2 and 1, respectively.

5. Results and discussions

In each simulation the inputs are \( V, f_1, \) and \( f_2 \); the considered outputs include current, power, heat losses, temperature deviation in the cross-section of the workpiece at the end of heating, and energy efficiency. The data obtained from 27 numerical experiments according to the DOE method was used to construct the relationships between inputs \( (V, f_1, \) and \( f_2) \) and outputs (energy efficiency and temperature deviation).

Figure 7 shows the graphical relations between the input factors and responses using RSM models. The
approximate equations of the responses are as follows:

\[ \eta = a_0 + a_1 f_1 + a_2 f_2 + a_3 V + a_4 f_1^2 + a_5 f_2^2 + a_6 f_1 V + a_7 f_2 V \]  

\[ \sigma = b_0 + b_1 f_1 + b_2 f_2 + b_3 V + b_4 f_1^2 + b_5 f_2^2 + b_6 f_1 V + b_7 f_2 V \]  

The coefficients of equations (15) and (16) were determined by a regression method.

Figure 8 shows the main effects of frequency \( f_1 \), frequency \( f_2 \), and voltage \( V \) on energy efficiency. The results show that decreasing the voltage and increasing the frequencies causes the energy efficiency to increase. However, voltage and frequencies have a complex effect on temperature deviation. Low or too high voltage results in high temperature deviation (Fig. 8a).

Because the frequencies and voltage have a reverse effect on the energy efficiency and temperature deviation, the multi-objective optimization problem has no single or unique optimal solution. Figure 9 shows the Pareto plot obtained by engineering data mining, in which the data file is collected from the solution of the NSGA2 algorithm. The maximum energy efficiency is 76.8%, and the minimum energy efficiency is 65.3%. However, if we choose the better energy efficiency, the temperature deviation is getting worse. We can decide the final solution based on this Pareto plot. We want high energy efficiency and moderate uniform temperature; therefore, the optimal solution was selected as shown in Figure 9. The optimum values of voltage \( V \) and frequencies \( f_1 \) and \( f_2 \) are 450 V, 978 Hz, and 1057 Hz, respectively. In this case, the energy efficiency is 73.5%, higher than the worst case 73.5 - 65.3 = 8.2%. It can be seen that process parameter optimization easily helps us to increase the energy efficiency.

6. Conclusions

This work presents an efficient approach for improving the energy efficiency of the induction heating process by applying process parameter optimization. Instead of focusing on improving the hardware or equipment (such as power supplies, inverters, or induction coils that were made by the induction heater manufacturer), we aim to optimize changeable process parameters such as voltages and frequencies of the heaters in the induction heating using a scientific approach and an elaborated study rather than practice or experience. To save experimental costs, the numerical simulation method was used as a preliminary investigation instead of performing a set of expensive physical experiments. This paper applied a computer-aided optimization approach in conjunction with DOE, metamodel, and multi-objective optimization based on a GA technique to systematically optimize the induction heating process parameters. The results show a practical benefit of optimizing the heating process parameter in terms of energy efficiency. Although a particular case study is explored, the approach of process parameter optimization can be applied to others manufacturing processes such as injection molding, machining, etc. with the same procedure.
Acknowledgements
This work was supported by Nha Trang University (2013).

References