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Analysis and reduction of coil temperature rise in electromagnetic forming

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ABSTRACT

How to reduce the temperature rise of coil winding is an important issue for improving the production and lifetime performance of the tool coil in electromagnetic forming system. To address the problem, this paper proposes a new discharge circuit configuration with a crowbar circuit to control the discharge current flowing in the tool coil and then to reduce the Joule heating generated without affecting the forming efficiency. A detailed numerical analysis of the mechanism of the temperature rise reduction was first carried out, and then numerical simulation and experimental investigation of the effects of the crowbar circuit on the coil current and surface temperature rise were investigated. The simulation results show that the Joule heating in the coil winding can be reduced from 4.62 kJ to 2.07 kJ when a crowbar circuit with a resistor of 0.3 Ω was applied, and the corresponding temperature rise in the coil can also be effectively reduced. Meanwhile, the experimental results show good agreements with the simulation results, further verifying the effectiveness of the proposed method.

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1. Introduction

Electromagnetic forming (EMF) is a high-speed forming technology by use of a pulsed electromagnetic force to reshape electrically conductive workpieces, which has been well known with a lot of published research dating back to the 1960s. The EMF process has several advantages in comparison to conventional quasistatic forming processes, such as improvements in performance including formability, wrinkling and spring back (Psyk et al., 2011). And consequently it has shown promise in overcoming the problems of forming lightweight metals that are difficult to shape.

In the EMF process, an intense transient electrical current was firstly applied to a coil through rapidly releasing a significant amount of electrical energy from a capacitor. At the same time a pulsed magnetic field was generated in the space around the EMF system and an eddy current will be induced in the conductive workpiece. Then a strong repulsive electromagnetic force can be produced to realize the rapid deformation of the workpiece. The forming performance, including the forming speed, range and depth, will increase with increasing electromagnetic force. However, further improvement has been restricted by two factors: (1) the mechanical loading of the tool coil. Similar with the electromagnetic behavior happened in the conductive workpiece, the intense electrical current flow in the coil and the magnetic field around will also produce huge electromagnetic force acting on the coil conductors. Thus the limited mechanical strength of the coil is one basic problem of the EMF system. To solve this problem and increase the tool coil life, our group has introduced the high-field pulsed magnet manufacturing technology, where internal reinforcement with high strength materials are inserted between the conductor layers, to increase significantly the strength of the tool coil for forming large and thick sheet metals (Qiu et al., 2012). The basic improvement mechanism is that the strength of the coil is mainly dictated by the reinforcing material that has much higher strength than common conducting materials with the help of reinforcement. (2) The thermal loading of the tool coil. It is illustrated in many researches that a significant part of the initial charging energy will be generated in the tool coil because of Joule heating losses, which has been well discussed by Gies et al. (2014). The considerable energy dissipation in the coil can cause a significant temperature rise in the EMF process and will have bad effects on the physical properties of both insulating and conductive materials, which in turn can damage interlayer insulation and decrease the coil life, especially in the case of high volume production with short cycle times. To solve the problem,

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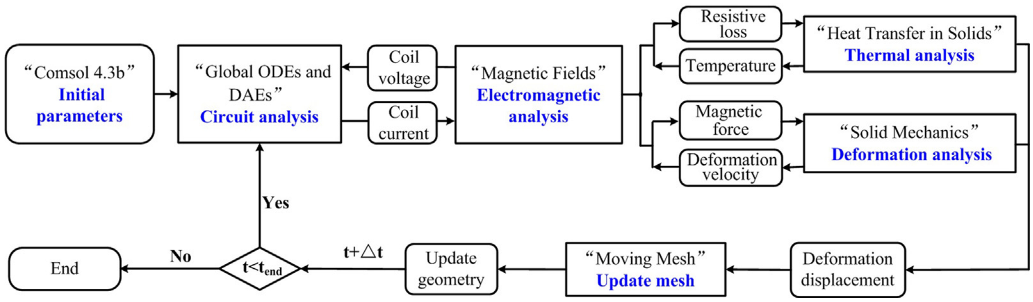

Fig. 1. Flowchart of the implemented algorithm.

Golovashchenko et al. (2006) developed an air cooling system in the EMF system which can provide the air flow along the coil surface for taking heat away from it. Unfortunately, the cooling system will introduce significant new levels of design complexity. Recently, Gies et al. (2014) made a detailed analysis of the coil temperature distribution and its influencing parameters (such as the workpiece material and cover layer thickness) in the EMF process by experimental and numerical studies. The obtained results are of practical value in optimizing the thermal characteristics of the coil to some extent. However, only limited improvement of the thermal problem can be achieved according to these results. More practical and effective solutions of the inevitable Joule heating effect in the EMF process should be developed and analyzed.

This article is focused to mitigate the thermal issues of the tool coil in the EMF process by proposing a new discharge circuit configuration with a crowbar circuit. Crowbar circuits have frequently been employed in many pulsed power applications, such as electromagnetic (Giorgi et al., 1989) and electrothermal chemical launchers (Jin et al., 2001). They can conveniently performed several distinct advantages over the conventional circuits including increased life of the capacitors, increased energy transfer efficiency and effective pulse shaping (Dethlefsen et al., 1993). Up to now, there are various kinds of crowbar circuits which have been well summarized by Jin et al. (2004) and the most common way is to install high-power diodes in parallel with the capacitor, which can automatically turn on the crowbar circuit upon voltage reversal. In the paper, the crowbar circuit consisting of a diode and resistor is used to adjust the discharge current and thus to change the Joule heating generated in the tool coil. Since the aim of the solution is to decrease significantly the thermal loads of the tool coil without bringing negative influence to the forming performance, the effects of the new circuit system on the temperature and deformation behavior during the EMF process are both investigated. A detailed numerical analysis was first carried out by solving the coupled electromagnetic, thermal and mechanical problems based on an efficient finite element model, taking into account the skin effect on the temperature distribution, the influence of the sheet velocity and the interaction between the electromagnetic field and the evolution of the workpiece shape. And then the electromagnetic sheet forming experiments of AA5083-O were carried out to further validate the effectiveness of the proposed method.

2. FEA model of electromagnetic sheet forming

The EMF process is a rather complex process, where electromagnetic, structural and thermal parameters are tightly interwoven. To better understand the basic physical phenomena during the EMF process, a simple finite element model was developed to analyze the dynamic behavior of the workpiece in our previous work (Cao et al., 2014), taking into account the effects of the sheet displacement and velocity on the discharging current and the distribution of magnetic field. However, the thermal model was not considered in the simulation and the discharge current density was assumed to be the same in each turn of the coil without considering the skin effect of conductors.

In this paper, an improved finite element model has been developed for solving these issues and is used for investigating the electromagnetic, thermal and mechanical behavior of the EMF system with different circuit configurations. The schematic flowchart of the simulation method is illustrated in Fig. 1. By use of the COMSOL Multiphysics Software package (V4.3b), five physical models have been established in the simulation: (1) "global ordinary differential equations (ODEs) and differential algebraic equations (DAEs)" model, (2) "magnetic fields" model, (3) "Heat transfer in solids", (4) "solid mechanics" model and (5) "moving mesh" model, which are solved using a time-dependent fully coupled solver. The first four models are used for circuit analysis, electromagnetic analysis, thermal analysis and mechanical analysis, respectively. And the last model is taken to update the shapes of mesh elements with the deformation of the workpiece based on an arbitrary Lagrangian–Eulerian (ALE) method. With the proposed

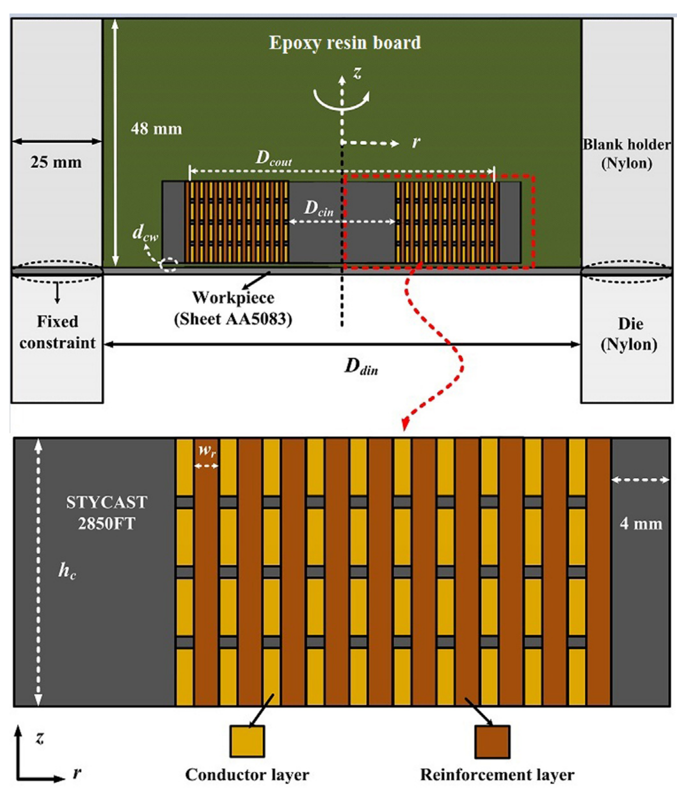

Fig. 2. Schematic geometry of the electromagnetic sheet metal forming system. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

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