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3-D ANIMATION OF MAGNETO-THERMAL COUPLED PROBLEM USING FEA

Vlatko Čingoski, Akihiro Namera, Kazufumi Kaneda and **Hideo Yamashita**
Faculty of Engineering, Hiroshima University, 1-4-1 Kagamiyama,
Higashi-hiroshima 739, JAPAN

Abstract: In this paper, 3-D animation of magneto-thermal coupled problem involving moving conductors is presented. The induction heating process of a moving steel billet is simulated using results obtained from two different solution spaces: a vectorial space based on edge finite elements for analysis of electro-magnetic phenomenon and a scalar space based on nodal finite elements for analysis of thermal phenomenon. Through 3-D visual animation, physical behavior of the coupled problem can be easily understood, and CAD/CAM processes can be further simplified by making design and analysis of such complex magneto-thermal coupled problems simpler.

1. INTRODUCTION

Magneto-thermal or magneto-mechanical coupled problems have appeared in various fields of engineering. Due to their complexity, however, acquiring of understanding of the physical mechanism, connections and influences among different magnetic, thermal and mechanical quantities involved in the coupled process has proven very difficult. To easily grasp relevant quantities and to understand their physical appearance, we must assist and improve the post-processing of the numerically obtained results.

In this paper, the authors utilize a sophisticated method of visual simulation and animation as a method for post-processing obtained results by numerical FEA of magneto-thermal coupled problem involving moving conductors. We use a continuous casting process for steel billets as an example. Since the temperature of the steel billet is too low for rolling and the temperature distribution inside the billet is not uniform, the induction heating process is usually used as a method for raising the billet's temperature. However, taking into account the time changes involved in the electromagnetic process resulting in eddy-current flow inside the steel billet and the rise in temperature, the entire coupled process becomes very complex. Finally, considering the movement of the billet inside the induction coils and the non-linear characteristic of some of the material constants, the problem of adequate treatment of the coupled problem becomes more significant.

First, we will give a brief explanation of the analyzed model and its peculiarities. Then, we will shortly discuss the numerical analysis method of the magneto-thermal coupled process using FEA. Afterwards, we will discuss the process of animation and its advantages as a sophisticated method for 3-D visualization of space and time changes of electromagnetic and thermal quantities involved in the coupled problem. The usage of the *high-definition television* (HDTV) system will be also addressed as a sophisticated method to obtain a high-quality visual simulation of the analyzed physical phenomenon. HDTV 3-D visualization, due to its increased screen resolution and abilities to generate a nearly-realistic images of the analyzed process, becomes a very promising post-processing tool. Then, we will present the results obtained with some still-images of the 3-D animation we produced in addressing this problem. Finally, we will provide conclusions and some final remarks.

2. ANALYZED MODEL

Before we discuss in detail the method of analysis of magneto-thermal coupled process, the visualization process and animation of the obtained results, let us first briefly describe the process of continuous casting. The schematic diagram of the continuous casting process is presented in Fig. 1. After smelting of the steel inside the arc-furnace and its solidification using a water-cooled copper mold and a cold water spray technique, the steel is cut into billets with constant lengths and is sent further on for rolling. The temperature of the billet, especially on its surfaces and edges, is too low for rolling and the temperature distribution is not uniform. Therefore, a system of induction heating coils has to be established in order to raise the billet's temperature and make the temperature distribution more uniform. However, design and manufacturing of this induction heating system is not an easy task. To add to this process, which involves design of the induction coils and definition of the electrical parameters (current intensity and frequency), the velocity of the billet inside induction coils etc., we propose animation of the entire induction heating process using the previously obtained results during numerical analysis.

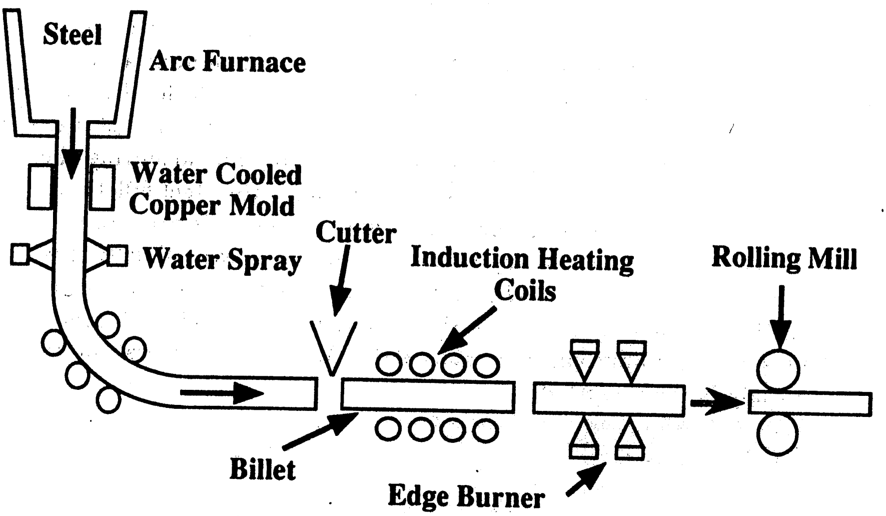

Fig. 1. Continuous casting process

Figure 2 shows the analysis model and the position of several observation points along the billet. The length of the steel billet was 5 $[m]$ and it moves inside the circular induction coils with a constant velocity of 12.5 $[cm/s]$. Regarding the speed of the billet, a time step of 1 $[s]$ was found suitable and 65 steps in total were necessary to simulate the magneto-thermal coupled process for the total length of the billet inside the coil region.

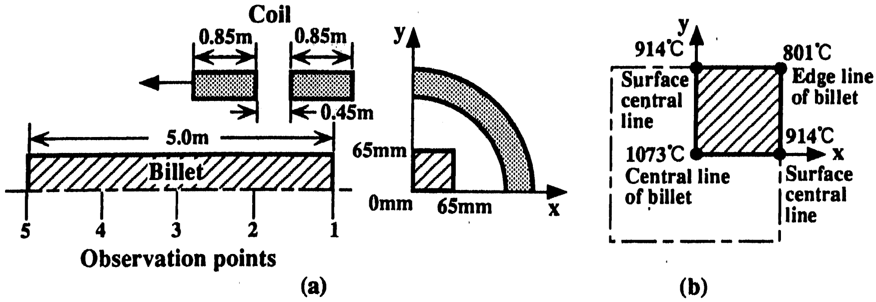

Fig. 2. a) Analysis model b) Initial temperature

3. METHOD OF ANALYSIS

In this paragraph, we explain briefly the method employed for numerical analysis of a magneto-thermal coupled problem with moving conductors.

3.1. Magnetic field analysis

Because of its vectorial character, analysis of the magnetic field distribution and subsequent eddy-current distribution were computed using the finite element method based on the vectorial (edge) type of finite elements [1], [2]. These types of finite elements were also chosen in order to minimize the computational time and memory requirements for such an intensive analysis involving time changes and moving conductors. In order to maintain a high accuracy of the obtained results 3-D finite element meshes with appropriate mesh densities especially around billet's surface area were developed. Instead of a moving conductor and static induction coils, we developed a model with moving coils and a static conductor, achieving the same physical effect with the development of only one division map. Since the steel billet, has a temperature higher than the critical Curie temperature for magnetic materials prior to entering inside the induction coils, the magnetic field analysis was treated as linear. Finally, the magnetic field analysis was performed only for several coil positions on both ends of the conductor and only for one coil position in the central area of the conductor. For each additional coil position in this area, the results were appropriately translated. As a result, several intermediate steps of magnetic field analysis were omitted.

3.2. Thermal field analysis

Due to its scalar characteristic, the thermal field analysis was computed using the finite element method with nodal finite elements. Using the distribution of the temperature on the surface of the billet as a result of the smelting process inside the arc-furnace and the constant heat dissipation through convection and radiation, the boundary conditions for the billet surface were computed using several empirical equations [3]. In the thermal field analysis, the generated heat due to the eddy-current flow and Joule losses inside the steel billet was treated as a heat source. Due to the non-linear characteristic of the heat-transfer coefficient, the Newton-Raphson non-linear process was considered. To obtain the time-dependent distribution of the thermal field we used the Crank-Nicolson recurrence formula. A simplified algorithm of the coupled magneto-thermal analysis is presented in Fig. 3.

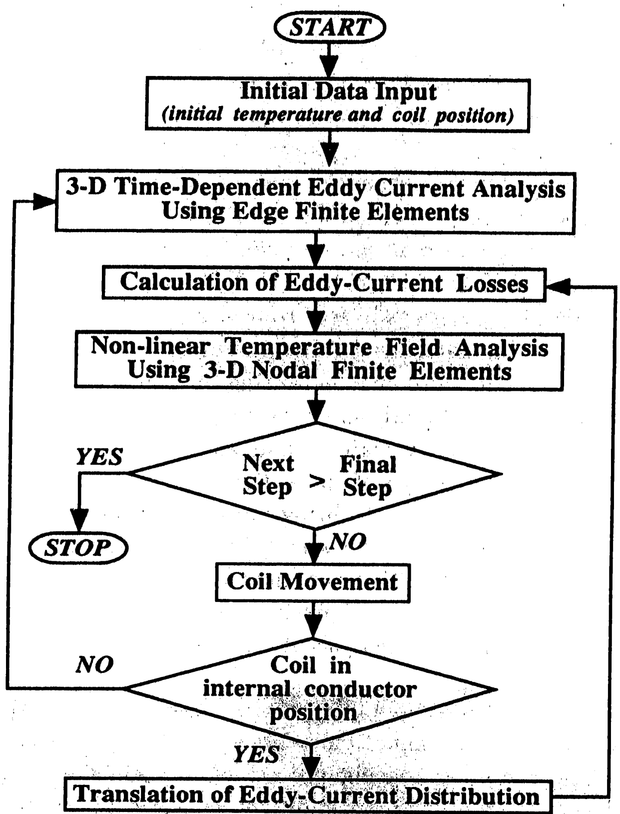

Fig. 3. Proposed algorithm

4. ANIMATION OF THE OBTAINED RESULTS

First, we define the main characteristics that the animation of analyzed magneto-thermal coupled process must satisfy:

- Physical insight to the electromagnetic phenomenon and the eddy-current flow inside the steel billet.
- Physical insight to the thermal phenomenon due to its initial non-uniform temperature distribution, edge and surface effects and the obtained temperature distribution due to the generated source of thermal energy inside the billet as a result of the enforced eddy-current flow.
- 3-D space and time changes of eddy-current and temperature distributions inside the steel billet.

- The influence of the geometry and parameters of the induction heating system and the moving velocity of the billet inside this system.

- Reality in the visualization of the coupled process and its animation.

The most effective method for obtaining a realistic insight into any time changing physical phenomenon, regardless of whether it is a time periodical or transient phenomenon, is the animation method. Two different approaches in the animation can be experienced: real-time animation and animation using a video tape recorder (VTR). Real-time animation is a very effective animation method, but unfortunately it always requires workstations with high-speed graphic engines which are rather expensive [4]. On the other hand, the visualization using a VTR is generated by storing information or sequences frame-by-frame on a VTR device and afterwards replaying them at normal (or slow) speed. This kind of animation enables definition of the same visualization parameters as in real-time animation such as view-depths, zoom, view point and its movement in 3-D space, perspective or isometric view, but much cheaper than real-time animation. VTR animation also enables editing of animation with other images or figures out of the scope of the numerical analysis or its obtained data representation. These images can give a deeper insight into the visualized and animated process. As an example, Fig. 4 shows a synthetically generated image of the entire continuous casting process. The purpose of this synthetically generated image is to bring more reality into the animation process and a simplified understanding of the process we would like to visualize. Recently, with development of the high-definition television (HDTV) where near-realistic images can be generated due to an increased screen resolution and number of pixels, the animation process becomes an extremely powerful method for presentation and analysis of very complex physical problems such as coupled problems.

We developed a HDTV 3-D video animation of the magneto-thermal coupled process involving moving conductors. The entire animation sequence is approximately 3 *min* and 20 *s* long and presents the entire induction heating process of a steel billet including its eddy-current and temperature distributions. The animation consists of eight scenes including the opening and closing. Each scene deals with different aspects of the induction heating process and its consequences. Also, some synthetic images were generated (see Fig. 4) in order to improve animation insight. During the numerical analysis, it was found that the temperature increase on the front and back surfaces of the steel billet was too great. This fact resulted in the inclusion of magnetic shields on the front and back side of the induction coil. Eddy-current and temperature time distributions for a model with shields and for one without shields are presented, and therefore shield effects can be easily understood. Finally, two still-images from the HDTV 3-D animation are presented in the following Figs. 5 and 6 in order to verify the usefulness of animation as an analysis and design tool. Due to publication problems, the still-images presented in this paper are black and white, although the real HDTV 3-D animation is color.

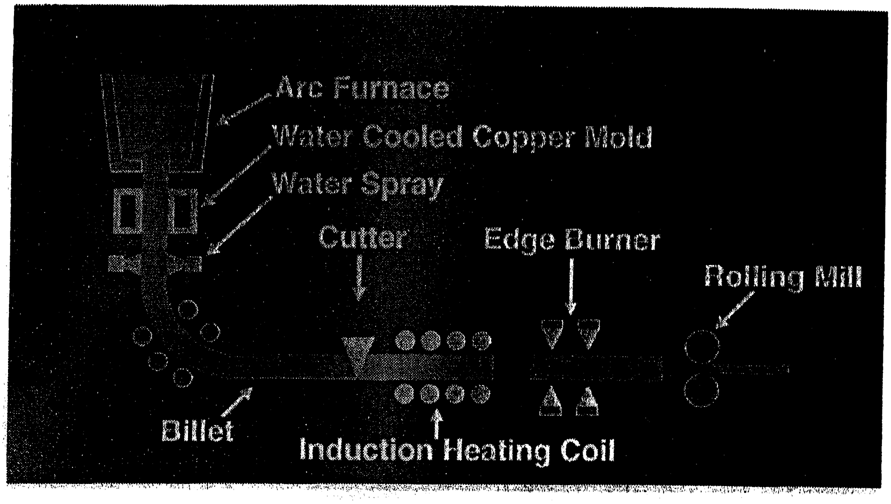

Fig. 4 Synthetically generated image of continuous casting process

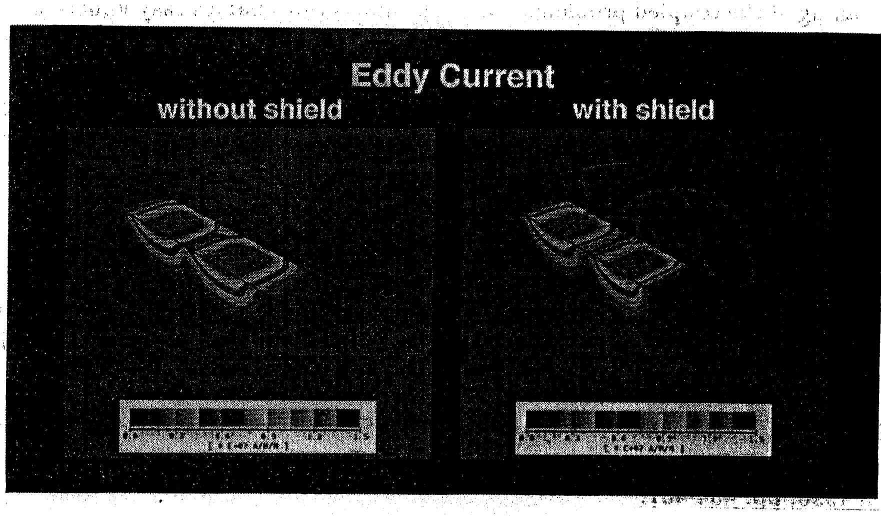

Fig. 5 Still image of eddy-current distribution

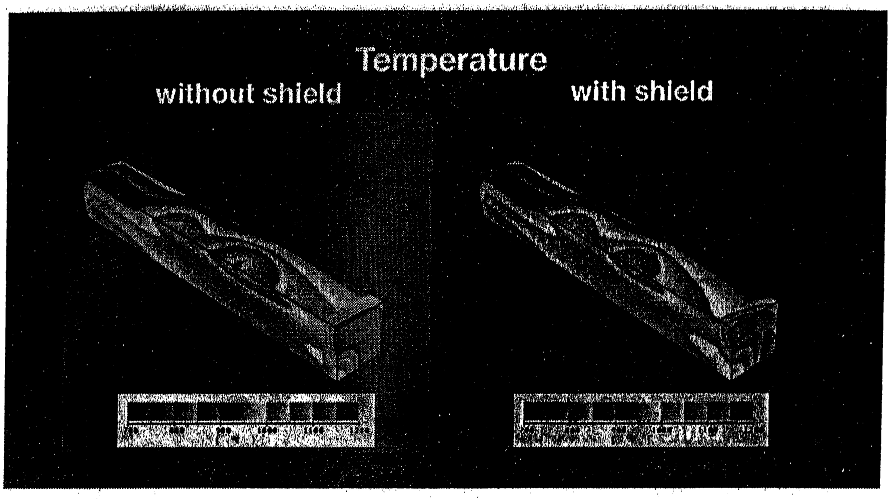

Fig. 6 Still image of temperature distribution

5. CONCLUSIONS

An animation method for post-processing of the magneto-thermal coupled process involving moving conductors is presented. The method provides easy insight into the rather complex physical meaning of the coupled problems. Also, the animation enables easy understanding of the numerically obtained results and analysis of the influence between different magnetic or thermal quantities. Using HDTV 3-D animation, near-realistic images of the obtained phenomenon can be achieved, which is very beneficial for analysis of already produced designs and designs of new coupled devices, regardless of whether they are magneto-thermal, magneto-mechanical or any other type.

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