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Thermo-mechanical analysis of line heating process by an efficient and accurate multi-level mesh refining method

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ABSTRACT

Plate forming technique with line heating is indispensable for producing curved plates of ship hulls. The present study aims to reduce the tremendous computation time in transient thermal-mechanical analysis of line heating with a moving heat source. The dynamic mesh refining method developed by the authors was extended to simulate large scale plate forming process by line heating. The current method features an element orientation-based multi-level refinement scheme which greatly reduces the number of degrees of freedom in a finite element model. Meanwhile, the background mesh introduced in the dynamic mesh refining method was used to save and update global solution. Accuracy of the refining method was demonstrated by parallel line heating on a square plate with available experimental results. Furthermore, the performance of proposed method was examined through comparison with a general purpose commercial code. It was confirmed that, the new code has comparable accuracy while the computational efficiency is more than one order higher than the commercial code. The transient thermo-mechanical analysis of line heating on a large-scale plate was accomplished within a realistic time.

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1. Introduction

Line heating is an important plate forming technique as it can be used to bend flat plates into desired complex shapes [1]. On the other hand, line heating can be employed to correct excessive welding deformation and even buckling distortion [2]. However, perhaps due to the complexity of the plate forming process, line heating is still carried out by experienced workers in many industries such as steel construction and shipbuilding. In order to automate the process, researches on theoretical models and numerical approaches were carried out in past three decades. Moshaiov and W. S. Vorus [3] presented a theory for thermo-elastic-plastic plate bending, and the difference between plate and beam bending mechanisms was shown. Nomoto [4] proposed a simplified nonlinear elastic model for bending of thick plates, and a simulator system was developed. Shin [5] and Moshaiov [6] presented a modified strip model for analyzing the line heating of elastic plates and thermal-elastic-plastic plates.

Ueda and Murakawa ([7–10]) conducted a series of work on computer-aided process planning system for plate bending by line heating based on the concept of inherent strain. With these knowledge, an automated plate bending system IHI-α had been developed (Tango [11]). Shin et al. [12,13] also designed an automatic line heating system which included processes such as shell modeling, shell development, heating information computation, and surface comparison. More recently, a fully

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automated system IHIMU-α for line heating had been developed at IHI (Tango [14]). In this system, the heating plan for a target shape was determined with the aid of inherent strain method. Articulated robots for handling the heating coil, adaptive plate supporting jacks, and a plate turn-over device were also introduced to replace the manual operation. The system could deal with plates with a thickness of 12–25 mm.

In general, the simplified models have difficulties in considering the influential factors such as the edge effect (Vega [15]) and the crossing effect (Vega [16]) which are necessary for accurate simulation of deformation induced by line heating. Further, thick plates differ from thinner plates apparently in aspect of mechanical response and inherent strain distribution. As a straightforward numerical approach, 3D thermal elastic-plastic finite element method (TEP-FEM) can be utilized to perform a complete simulation considering these effects. Further, TEP-FEM can also provide information of residual stresses (Deng [17]) which are vital for evaluation of ultimate strength and fatigue strength.

Nevertheless, computations with TEP-FEM usually take large amount of time due to the high nonlinearity and long duration of transient thermo-mechanical processes. Several efforts have been contributed on analysis methodology to enhance the performance of computation. The iterative substructure method (ISM) was proposed by Murakawa [18] from the viewpoint of solving highly nonlinear regions separately from linear or moderately linear regions. The method has been proved to be efficient and robust. Adak and Mandal [19] proposed a pseudo-linear method for analysis of line heating problems. The initial nonlinear problem was transformed into a linear system with constant stiffness. In addition, remeshing techniques were combined with TEP-FEM in welding simulation. Surana [20] presented a finite element formulation for 3D p-version hierarchical curved shell element to solve heat conduction problem. Nevertheless, the application of such a shell element formulation to thermal mechanical problems were not reported yet. Brown and Song [21] presented the rezoning method and substructure method using shell model for simulation of laser heating. Lindgren [22] employed the graded element with variable nodes to simulate the electron beam welding of a large copper canister in 3D model. Duranton [23] analyzed a multi-pass welding of a stainless steel pipe with adaptive mesh refinements. Though qualitative results were obtained by using above remeshing techniques, quantitative comparison between analysis with and without remeshing were not found. These remeshing methods introduced mesh coarsening behind the heat source, which is supposed to cause inevitable error to the analysis. Because the detailed solution on fine elements especially thermal and plastic strains can not be transferred accurately to coarse elements by mapping. The stress and strain usually have much more complex distribution than temperature and displacement. A coarse element cannot carry the same detailed information as several fine elements do. The mapping induced error becomes larger when multi-level refinement is employed.

In order to keep the solution accuracy, Huang and Murakawa [24] developed a dynamic mesh refining method (DMRM). In this method, a background mesh was employed to save and update the solution of stress and strain. Recently, the DMRM was extended to refinement in multi-level hierarchical mode with a feature of element orientation dependence. In the present study, the flow chart of multi-level mesh refining was shown in detail. The analysis on background mesh was also supported in order to get high resolution of stress and strain under large deformation theory. An experimental model of parallel line heating on a square plate was analyzed by the proposed method. Transient temperature and residual deformation were compared between measurement and simulation. In addition, two numerical examples of line heating on larger plates were examined in the present study. Firstly, a twisting type line heating model was analyzed, and a comparison between the in-house code DMRM and a general purpose code ABAQUS was made to examine the accuracy and efficiency of the proposed method. Secondly a rectangular plate with 33 heating lines was simulated by the proposed new approach to demonstrate its performance on industrial scale models.

2. Thermo-mechanical analysis of line heating

2.1. Heat source model

In the case of line heating, heat input prediction of gas torch was experimentally investigated by Osawa [26,27]. For simplicity, the Gaussian surface heat source model as shown in Fig. 1 was employed in this research. The distribution of heat flux q_s is described by the following equation:

$$q_s = \frac{3Q}{\pi r_e^2} e^{-3\left[(x-x_0)^2+(y-y_0)^2\right]/r_e^2} \tag{1}$$

where Q is the net heat input per unit time from the heat source, r_e is the characteristic radius. x, and y are global coordinates of a point at which heat flux is to be evaluated, and x_0, and y_0 are coordinates of the heat source center at the current time.

2.2. Thermal analysis

A decoupled thermal mechanical analysis scheme was adopted due to the extremely small heat effect of the mechanical process on the thermal one in line heating. Firstly, thermal analysis was carried out, and temperature history results were saved. Then, mechanical analysis was carried out with reading temperature to form thermal load at a transient time.

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