Simulation of welding thermal conduction and thermal stress using hybrid method of accelerated explicit and implicit FEM

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Abstract. A hybrid method combining the accelerated explicit and the implicit FEM was developed for simulation of welding thermal stress. Furthermore, to reduce the computing time and keep the simulation accuracy, the hybrid modelling using solid elements around the welded zone and shell elements in the zone away from the welded zone is recommended. The applications of hybrid method and hybrid modelling to the simulation of welding thermal conduction, thermal stress and strain showed a good efficiency.

1. Introduction
The simulation of welding induced thermal stress by Finite Element Methods (FEM: Finite Element Methods) was started from the 1970s and has about more than 40 year history [1]. Since then, static implicit FEM combined with the thermal elastic-plasticity theory has been used as a general method for the simulation of welding deformation and thermal stress [2]. In recent years, some new schemes such as ISM (Iterative Substructure Method) [3] and modified ISM [4-5] have been developed in order to speed up the calculation. On the other hand, dynamic explicit FEM was also proposed and developed since the 1970's. It is generally employed for the simulation of the short time dynamic behavior such as impact mechanics [6]. Concerning with the simulation of the welding thermal stress using the dynamic explicit method, it is necessary to utilize velocity scaling technique and mass scaling technique [7-8].

The static implicit method FEM is efficient in simulating a long-time physical phenomenon since a large time increment is allowed. However, when the degree of freedoms to be analyzed reaches up to the order of millions or more, the memory requirement for the computation becomes large and this may make many simulation works to be incomputable on personal computers. For this reason, the explicit FEM with small memory usage was paid attention [7-8]. Recently an idealized explicit method [9] and an accelerated explicit method [10-11] specialized for analysis of welding thermal stress and thermal strain have been proposed. However, if the explicit method is used to reproduce global bending deformation of structures with large dimensions, the number of calculation cycles increases and the computation time will be long. Therefore, to shorten the computation time of explicit FEM, we developed a parallel computing program using GPU (general purpose Graphic Processing Units) and made the computation become much more efficient [9-11].
Considering the advantage of the accelerated explicit FEM in the simulation for short-time dynamic phenomenon with the strong nonlinearity of thermal stress in the heating process and the advantage of the implicit FEM for the static mechanical behavior during the long-time cooling process in welding, we proposed a hybrid method by combining explicit FEM and static implicit FEM, and then developed a research program JWRIAN-hybrid. Through performing simulations on welding deformation and residual stresses, it can be found that the computation efficiency was greatly improved. At the same time, we developed an iterative scheme based on Newton-Raphson method and speed up the computation of transient thermal conduction analysis. Finally, we applied the hybrid method to the analysis of transient thermal conduction, thermal stress and welding deformation induced by the arc-welding.

2. Hybrid method combining ISM implicit and accelerated explicit FEM

To easily explain the features of the high speed ISM implicit FEM, the accelerated explicit FEM and the hybrid method, we will focus on the basic concept without using complicated formulas in the followings.

2.1. ISM implicit FEM

The implicit FEM based on thermal elastic-plastic theory uses following equation in which \( \{\Delta F\} \), \( \{\Delta u\} \) and \([K]\) are the vector of the equivalent nodal force increment, the vector of the nodal displacement increment and the stiffness matrix of the analysis model, respectively.

\[
[K]\{\Delta u\} = \{\Delta F\}
\]  

When welding thermal cycles at all nodes of the FE model are obtained by performing thermal conduction analysis previously, the nodal force increment \( \{\Delta F\} \) can be easily computed from the temperature increment and material properties such as thermal expansion coefficient, Young’s modulus, Yield stress and hardening coefficient. When the stiffness matrix \([K]\) is assembled from matrix computed in each element, the unknown displacement increment \( \{\Delta u\} \) can be obtained by solving the equation (1).

However, the total number of components of the stiffness matrix \([K]\) is large, so the computation time will be very long and the memory usage will be large. Therefore, how to speed up the computation of implicit FEM and how to reduce the memory usage are important issues in computational science and engineering.

When structural components or plates are joined by welding, the high-temperature region including the melting zone shown in Fig. 1 is much smaller than the dimension of the base metals and the dynamic nonlinearity is strong in this zone. On the other hand, the region with the low temperature is wide, but the mechanical behavior is linear. Utilizing this feature, the ISM (Iterative Substructure Method) has been proposed, and the computing efficiency for welding induced thermal stress has been significantly improved [3-5].

![Fig.1 Local nonlinear region A and linear region B in global model G.](image)
2.2. Accelerated explicit FEM

The equation of motion of dynamic explicit method is given by equation (2). In the equation, $[M]$ is the lumped mass matrix of the nodes of FEM, $\{F_{ext}\}$, $\{F_{int}\}$, and $\{F_{damp}\}$ are the equivalent external nodal force, internal nodal force and damping force, respectively.

$$[M][a(t+dt)] = \{F_{ext}(t+dt)\} - \{F_{int}(t)\} - \{F_{damp}(t)\}$$ (2)

Since the mass matrix $[M]$ in above equation has only the diagonal component, the acceleration $\{a\}$ can be easily calculated. However, to get the accurate solution by above equation, the time increment $dt$ must be small enough according to Courant-Frederic’s-Lewy Condition [31].

$$dt = \frac{Le}{c}$$ (3)

Where, the $Le$ in above equation is the minimum length of all elements and $c$ is the stress propagation speed given by following equation.

$$c = \sqrt{\frac{E(1-\nu)}{(1+\nu)(1-2\nu)} \frac{1}{\rho}}$$ (4)

Where, $E$, $\nu$ are the Young’s modulus and Poisson’s ratio of materials.

In the accelerated explicit method (ACEXP), we use the accelerated time domain $t^{ACEXP}$ to replace the real time domain $t^{real}$ and then convert the thermal cycle from the real time domain to the accelerated time domain, as shown in Fig.2.

![Fig.2 Welding thermal cycle in real time domain and accelerated explicit time domain.](image)

2.3. Hybrid method

The concept of a hybrid method for the simulation of welding thermal stress and deformation is schematically shown in Fig.3. Considering the strong nonlinearity of dynamic phenomenon in heating stage of welding process, the stable acceleration explicit FEM is selected for analysis of the transient thermal stress and strain. During the cooling stage of welding process, materials around welded zone become stiff and thermal mechanical nonlinearity becomes weak, the implicit FEM can easily give convergent solution even at a large time increment.
3. Hybrid modelling using solid elements and shell elements

Generally, the thickness of base metals to be welded is quite small compared with the dimensions of the welded structure. Therefore, thin shell elements are often used in the strength analysis of structures. However, the thermal and mechanical phenomena around welding zone are very complicated, solid elements are preferred in the simulation to achieve the high accuracy. For these reasons, we proposed a hybrid modelling for efficient simulation of welding thermal conduction and thermal stress with the aid of solid elements including the 8-node hexahedral element, the 6-node penta element, the 4-node tetrahedral linear tetra element, the 10-node tetrahedral secondary tetra element, the 4-node tetrahedron secondary tetra element, and shell elements such as the 4-node quadrilateral shell element, the 3 node triangle shell element, as shown in Fig.4.

4. Simulation of welding thermal conduction and thermal stress using hybrid method

The welded joints shown in Fig.5 were taken as examples in simulating the welding thermal conduction and thermal stress using hybrid method and hybrid modelling. The comparison of computation time among explicit FEM, implicit FEM and hybrid method for heating and cooling stages in welding process is shown in Fig.6. The computation time of solid element modelling and hybrid modelling is shown in Fig.7. The hybrid method and hybrid modelling accelerated the computation greatly.
Fig. 5 welded joints and FE models used in simulating welding thermal conduction and thermal stress.

Fig. 6 Comparison of computation time among explicit FEM, implicit FEM and hybrid method.

Fig. 7 Comparison of computation time between of solid element modeling and hybrid modelling

5. Conclusions
(1) A hybrid method combining accelerated explicit and implicit FEM and its research software JWRIAN-hybrid were developed for simulation of thermal-mechanical phenomena.
(2) Hybrid modelling using both shell elements and solid elements was proposed and implemented into new research software.
(3) Computation time can be greatly reduced using hybrid method and hybrid modelling.
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