VIII International Conference on Computational Plasticity
COMPLAS VIII
E. Oñate and D. R. J. Owen (Eds)

PARALLEL PERFORMANCE EVALUATION OF MULTI-SCALE FINITE ELEMENT ANALYSIS BASED ON CRYSTALLOGRAPHIC HOMOGENIZATION METHOD

Hiroyuki Kuramae*, Kenji Okada*, Michinori Yamamoto*, Masanori Tsuchimura†, Hidetoshi Sakamoto† and Eiji Nakamchi*

* Osaka Institute of Technology
5-16-1, Omiya, Asahi-ku, Osaka, Japan
e-mail: kuramae@dim.oit.ac.jp, web page: http://www.oit.ac.jp

† Kumamoto University
2-39-1, Kurokami, Kumamoto, Japan
e-mail: sakamoto@mech.kumamoto.ac.jp, web page: http://www.kumamoto-u.ac.jp

Key words: Multi-scale analysis, Parallel processing, Crystallographic homogenization method.

Summary. *Since the multi-scale finite element analysis (FEA) requires large computation time, development of the parallel computing technique for the multi-scale analysis is inevitable. A parallel elastic/crystalline viscoplastic FEA code based on a crystallographic homogenization method has been developed using PC cluster. Since the dynamic explicit method is applied to this analysis, the analysis using micro crystal structures computes the homogenized stresses in parallel based on domain partitioning of macro-structure without solving simultaneous linear equations. In order to improve parallel performance of elastoplasticity analysis, which dynamically and partially increases computational costs during the analysis, a dynamic workload balancing technique is introduced.*

1 INTRODUCTION

Recently, the finite element analysis (FEA) to predict the failure and earing in the deep drawing operation with high accuracy is strongly required. The crystallographic homogenization method has been utilized as one of the effective numerical techniques [1-3]. However, the crystallographic homogenization FEA needs much computation time because of multi-scale and crystalline viscoplastic analysis.

In this study, a parallel analysis method for the crystallographic homogenization FEA has been proposed and implemented on PC cluster system. This parallelization method is based on the dynamic explicit method and using the message passing interface (MPI) library. The explicit time stepping solution in nonlinear finite element dynamics is well-suited to the parallel computing on the distributed memory environment because solving simultaneous equation is not required. This paper describes effect of parallel computing and dynamic workload balancing technique based on estimation of parallel computation time and some three-dimensional sheet forming analyses.

2 CRYSTALLOGRAPHIC PLASTICITY FINITE ELEMENT ANALYSIS

A three-dimensional polycrystalline macro-continuum is formed by periodic microscopic structures of a unit cell (RVE) as shown in Fig. 1. The region, Y, of the unit cell is made up of an aggregate of well defined crystal grains.

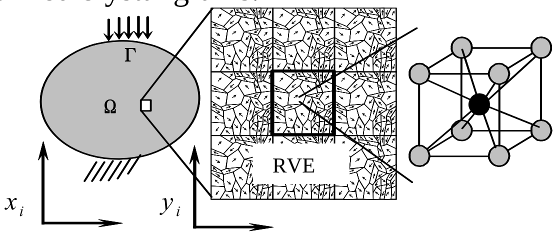


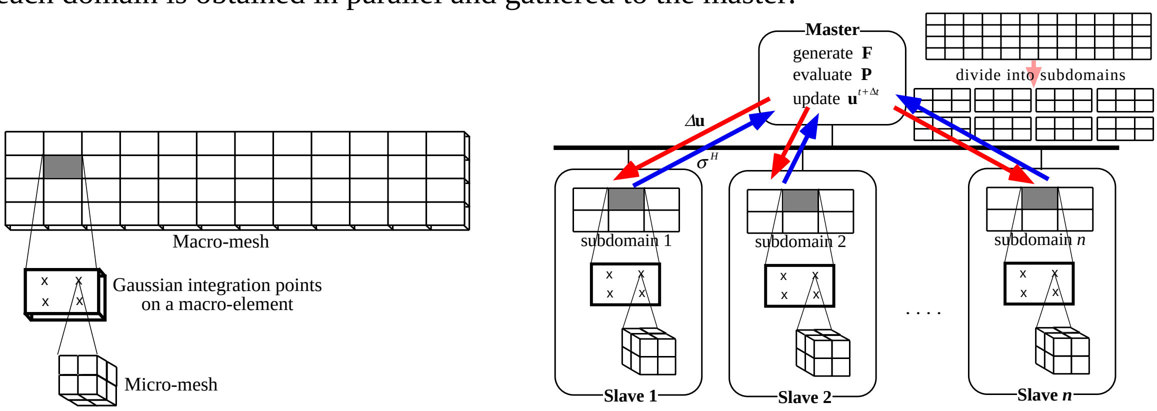
Figure 1: Macroscopic continuum and micro-structure.

To obtain the Cauchy stress tensor of macro-continuum, a finite element analysis of the unit cell is performed with consideration of the crystal plasticity. Since only geometry conditions are considered, homogenized stresses for the macro-continuum can be obtained using average of the stress for the unit cell.

3 METHOD OF PARALLEL COMPUTING

In this study, the dynamic explicit method is applied to the equilibrium relation. In order to obtain the internal force vector, the macro-scopic stresses are required on each Gaussian integration points using finite element analysis of micro-mesh as shown in Fig. 2(a). Therefore, the most of the computation time is consumed in the homogenized stress using micro-mesh.

To perform parallel computing, the whole region of macro-continuum is divided into the domains and allocated to cluster node as shown in Fig. 2(b). A master of the cluster nodes broadcasts the incremental displacement vector to all slaves. The homogenized stresses σ^H on each domain is obtained in parallel and gathered to the master.



(a) Hierarchical structure of multi-scale analysis (b) Schematic diagram of parallel analysis system.

Figure 2: Multi-scale analysis and parallel computing.

In order to improve parallel performance, dynamic workload balancing mechanism, in which subdomain allocation to slave is performed automatically and dynamically during analysis, is needed. Adaptive workload allocation method is proposed for elastic-plastic analysis. Number of macro-finite elements in subdomain is adapted for balancing the computational load among slaves. Adaptation process is performed at intervals by monitoring the computation time on all slaves during step-by-step solution. When subdomain size is adapted, computation history of micro-structure is communicated among slave machines.

4 EVALUATION OF PARALLEL PERFORMANCE

4.1 Estimation of Parallel Computation Time

Execution time of the parallel analysis can be expressed with some basic parallel parameters, which are the number slave machines n_s, the number of elements n_e and that of nodes n_p of macro-continuum. Upon adding communication time T_b, T_c and computation time T_s, T_m according to the time chart of the parallel analysis, we can establish the expression of the total parallel execution time:

$$T = \left(T_b + T_s + T_c n_s + T_m\right) I_t = \left\{\alpha_s \frac{n_e}{n_s} + \beta_b n_s + \left(\alpha_b n_p + \beta_b + \alpha_c n_e + \alpha_m n_p\right)\right\} I_t \tag{1}$$

where I_t is number of time steps. Since the first term is dominant in Eq. (1), the parallel execution time is inversely proportional to the number of slave machines.

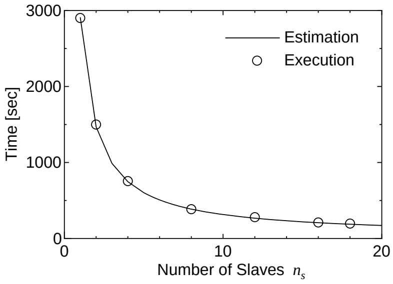
To verify the Eq. (1) for the parallel execution time, the comparison is made between the estimation and execution time for a sample problem (352 macro-elements and 8 micro-elements) with different number of slave machines. As shown in Fig. 3(a), the estimation time for elastic analysis agrees very well to the real execution time.

Estimation of parallel analysis time with different number of elements of micro-FE model is performed. Estimated speed-up factors by number of slaves are illustrated in Fig. 3(b). Since number of elements of micro-FE model indicates resolution of micro-structure, computation time on slave machines is increased by the number of elements. However, amount of data for communication is not depended on the number of elements because calculated stresses on micro-structure is homogenized in micro-FE mesh. Therefore, parallel performance is increased by number of elements of micro FE model.

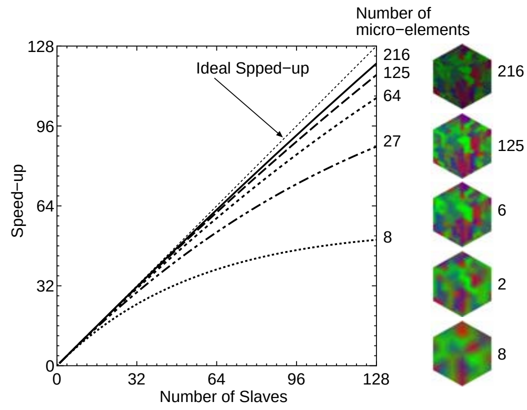
4.2 Parallel Sheet Forming Analysis

A limiting dome height (LDH) test is computed. The dome is formed by stretching a flat sheet over a hemispherical punch. Number of finite elements of macro-continuum and micro-structure are 448 and 27 (3×3×3), respectively. Material property is AL6022-T43 (Alcoa) is used.

Parallel performance and workload distribution on slaves are shown in Fig. 4. Ideal speed-up is archived in this parallel analysis.

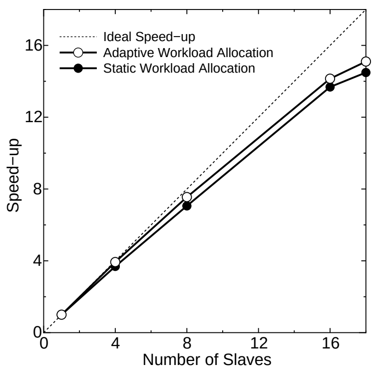


(a) Comparison between estimation and execution time

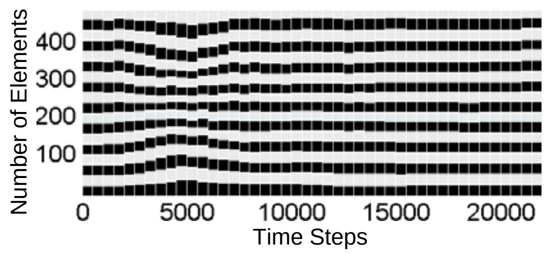


(b) Estimated parallel performance for various number of elements of micro-structure.

Figure 3: Parallel Analysis time.



(a) parallel performance



(b) workload distribution (18 slaves)

Figure 4: Parallel analysis result of LDH test.

5 CONCLUSIONS

Parallel multi-scale FEA based on the crystalline homogenization method is evaluated. Adaptive workload allocation method is introduced and proved to improve parallel performance. Linear speed-up is achieved in parallel performance evaluation and some sheet forming analyses.

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