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PARALLEL COMPUTING ALGORITHM FOR ROLLING OF SLABS WITH SEMI-SOLID ZONE

ALGORYTM OBLICZEŃ RÓWNOLEGŁY DLA PROCESU WALCOWANIA SLABÓW ZE STREFĄ PÓŁCIEKŁĄ

Abstract

The paper presents an application of parallel object-oriented programming technique in modeling of rolling of steel plates with semi-solid zone. Due to limitations of available computer resources, a very accurate computation can sometimes be impossible or the time performance can be a barrier for practical application of complex sequential models. Taking advantage of parallel computing the authors have developed an algorithm allowing the computation using multiple processors, which is the main subjects of the presented paper.

Keywords: *parallel computation, computer simulation, numerical models*

Streszczenie

W artykule zaprezentowano obiektowo zorientowaną technikę obliczeń równoległych w zastosowaniu do procesu walcowania slabów ze strefą półciekłą. Ze względu na ograniczoną moc komputerów będących do dyspozycji technologów obliczenia wymagające dużej precyzji mogą być niemożliwe lub czas obliczeń staje się barierą w przypadku złożonych modeli sekwencyjnych procesów. Wykorzystując zalety obliczeń równoległych zaproponowano algorytm pozwalający na obliczenia z wykorzystaniem dostępnych procesorów, którego prezentacja stanowi głównym cel artykułu.

Słowa kluczowe: *obliczenia równoległe, symulacja komputerowa, modele numeryczne*

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1. Introduction

Due to limitations of computer resources available to technologists, a very accurate computation can sometimes be impossible or the computation time can be a barrier for practical application of complex sequential models. Sudden changes of strip temperature and significant temperature influence on steel mechanical properties are source of optimization difficulties, which have to be taken into consideration in computation process. The resulting computer programs require very long processing time and parallelization can be a solution of the problem.

Sequential numerical algorithms using scalar calculations do not allow easy migration to parallel computers with shared memory due to their high sensitivity to the data which they work on. An attempt to transfer this type of algorithms to parallel computers needs serious modifications. A key issue that allows obtaining the shortest possible computation time is to minimize the communication between cluster nodes because of the high cost of CPU time and network latency.

The program presented in the current contribution enables the analysis of phenomena accompanying the material deformation during rolling of slabs with mushy zone. The proposed algorithm assumes such a development of code segments working on each cluster node which guaranties even distribution of workload among all workstations. Presented algorithm has been implemented in C++ language.

2. Sequential model – thermal solution

Heat transfer is one of the main phenomenaaccompanying the hot rolling process which results in formation of temperature gradients inside the rolling zone and even outside of it. In the presented model, heat flow is considered in a particular area of the specimen. The discretization process leads to selecting a finite number of points inside the body. Certain temperature is attributed to each of the points (nodes). The set of all values of the temperature at all given points creates a space and time dependent temperature field $T = f(x, y, z, t)$. Heat transfer models were based on the solution of Fourier-Kirchhoff heat conduction equation [1, 2]. The solution is based on heat flux functional minimization, which includes relevant boundary conditions.

$$\chi = \int_V \left\{ \frac{1}{2}\left[k_x \left(\frac{\partial T}{\partial x}\right)^2 + k_y \left(\frac{\partial T}{\partial y}\right)^2 + k_z \left(\frac{\partial T}{\partial z}\right)^2 \right] - QT \right\} dV + \int_S \left(qT + \frac{1}{2}\alpha (T - T_0)^2 \right) dS \quad (1)$$

In (1) λ_i are anisotropic heat transfer coefficients, Q – heat generation, V – control volume, S – body surface, α – heat transfer coefficient and q – friction heat. In [3] one can find solution of this problem in two steps. The first one is based on the Fourier-Kirchhoff equation for steady flow of heat using the finite element method. The second step is generalization of the resulting stationary matrix equations obtained for the steady-state process with the help of the Galerkin residual method. In both cases, the system of equations to be solved can be represented in matrix form as (2):

$$\mathbf{K}\,\mathbf{T} = \mathbf{p}, \quad (2)$$

where:

K – is heat capacity matrix,
T – parameters vector of temperature fieldand,
p – the right hand vector.

3. Mechanical Model

Another model, the most important one for metal forming processes, is the material plastic behavior model. In the presented approach a three dimensional rigid-plastic model is required, which in the case of large plastic deformations at very high temperatures can give good results. The power functional resulting from variational formulation of the problem is non-linear in all cases, hence requires more computing power.

Application of finite element discretization to analysis of spatial rigid-plastic model involvesthe processing of large number of variational parameters. Hence, the calculation requires long computation time, but results in a solution which is consistent with experimental data for both simple and complex deformation zones.

The variational approach of the rolling process requires optimization of a power functional, which in general can be expressed in the form of equation (3):

$$W = W_\sigma + W_\lambda + W_t \tag{3}$$

where:

W_σ – is power of plastic deformation,
W_λ – incompressibility condition penalty power,
W_t – is the friction power.

The deformation process of steel in semi-solid state, depends on material density changes. In this case the condition of incompressibility, which is sufficient for deformation at lower temperatures, has to be replaced with more general condition of mass conservation [5].

The application of finite element method in case of metal forming processesresults in a finite set of velocity values. All of them are parameters of the body deformation field. Spatial discretization allows optimization of deformation fields for a certain time step. At the same time discretization of time is necessary to perform series of time steps under the assumption of constant strain field in each step. The incremental solution of the problem has to be constructed iteratively. Each iteration involves solving linearized system which can be expressed as a matrix equation (4):

$$\mathbf{K}\,\mathbf{v} = \mathbf{f}, \tag{4}$$

where:

K – is the structure stiffness matrix,
v – the nodal velocity vector,
f – the right hand vector.

The process is divided into time steps. In each step Δt the final shape of the body is calculated from its initial shape usingthe velocity field resulting from optimization of the functional given by (3).

4. The parallel algorithm for a cluster of workstations

Task parallelism is a decomposition of more complex issues into smaller, simpler sub problems. Such decomposition encountersnumerousobstacles concerning the criteria and method of task division. There is no universal silver bullet decomposition method. As a consequence individual analysis and selection of the optimal method [6] is required for any particular case. The finite element parallel solution requires a uniform domain decomposition between the cluster nodes. In case of model with distributed memory, an appropriate division of tasks is required. The division should minimize thecommunication overhead, therefore geometric decomposition of the finite element mesh was chosen.

Decomposition of the problemimposes both the way of storingthe equation system and the method of exchanging data between processors. The equation set for thermal and mechanical model has to be stored in sub-matrices a in a form reflecting the selected geometric distribution. Each processor stores the allocated part of matrix and right hand vector. Communication between cluster nodes with neighboring subdomains is essential for maintaining consistency of data common to the machines.

It is necessary to store data belonging to the neighboring subdivisions. This problem has been solved by the use of temporary data vectors. The same rules may be applied to both heat capacity and stiffness matrices. The stiffness matrix has larger number of variables so is able to store more data. Principles of data exchange and completion of local matrices are the same – the only difference makes amount of data.

5. Productivity analysis of modeling the steel rolling process in the semi-solid state

The developed parallel algorithm was tested on a cluster of two nodes. Each node had twoDual-Core AMD Opteron 2.2 GHz processors, 2048 MB of memory and disk matrix RAID 0 RAID CORE HT 1000, 2 × 400 GB and the operating system OPEN SUSE 10.2. Communication between cluster nodes was based on MPICH message-passing environment [7] over a 1 Gb/s Ethernet Network.

In order to determine efficiency and speedup of calculations, several tests have been conducted. The acceleration quality was calculated using the following indicators:

– relative speedup (5):

$$S_p = \frac{t_1}{t_p}, \tag{5}$$

where t_1 is the execution time on one processor and t_p execution time on p processors,

– efficiency (6):

$$E_p = \frac{S_p}{p}, \tag{6}$$

where S_p is the speedup and p number of processors.

The main part of computational tests was performed for parallel iterative methods for solving set of equations, CG and MINRES [8]. Program efficiency analysis was performed,

as well as tests of the solvers for 40,000 data nodes for two categories of parallel computing: shared memory and distributed memory models. Although many basic operations (object creation, memory allocation, mesh generation, solving the set of equations, results collection) could not be performed in parallel due to data dependence, conducted tests show the computational efficiency of the solution. In order to verify the performance of networks for computational process, tests were conducted for both the mentioned memory models. The results of the tests are presented in pictures 1, 2 and 3.

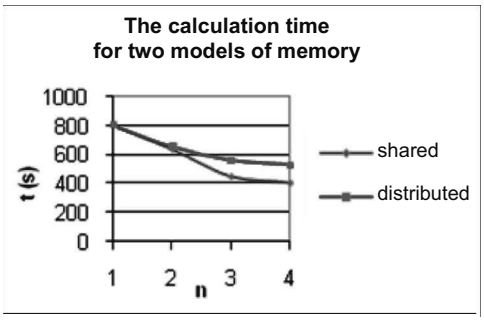


Fig. 1. Time profile for shared and distributed memory model
Rys. 1. Charakterystyka czasowa programu dla schematu pamięci dzielonej i rozproszonej

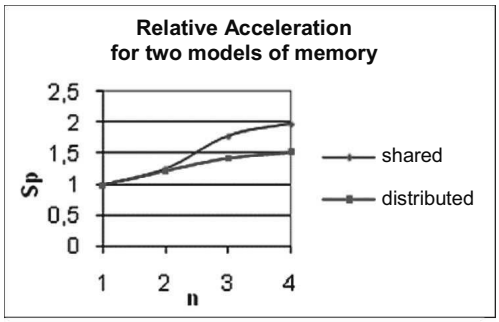
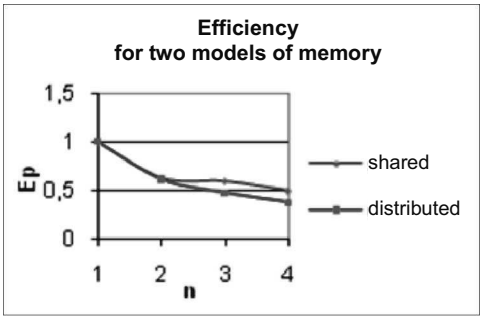


Fig. 2. Acceleration profile for shared and distributed memory model
Rys. 2. Przyspieszenia programu dla schematu pamięci dzielonej i rozproszonej



Rys. 3. Charakterystyki efektywności programu dla schematu pamięci dzielonej i rozproszonej
Fig. 3. Efficiency profile for shared and distributed memory model

The assumption of proposed methods of calculation and decomposition of the problem was thereuse of existing sequential source code to the maximum extend. Despite the partially sequential program, satisfactory rates of speedup for bothlocal and network communication methodshave been observed. The results show the comparison of computation time, speedup and efficiency for computers with different models of parallelism. Better computing performance has been observed for the model with shared memory due to much smaller communication overhead.

6. Conclusions

Parallelization of iterative methods for solving systems of equations was performed for the following operations: construction of a parallel matrix, the matrix-vector product, scalar product of vectors, vector's norm, preconditioning and implementation. Because all these operations work on independent parts of the matrix and vectors, their parallelization is very effective. Finally, a parallel version of the software simulating the rolling process of steel in semi-solid state was built. The acquired results allow the conclusion of the appropriateness of proposed solution.

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