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DEVELOPMENT OF A PARTICLE METHOD FOR ELASTIC AND CREEP DEFORMATION

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ABSTRACT

A new particle method for elastic and creep analysis is developed. This method is based on the concept of MPS (Moving particle semi-implicit) method which was developed for fluid dynamics. Particle interaction models for differential operators are prepared in MPS method. The governing equations of elastic structures are interpreted into interactions among particles. Using the present particle method, elastic interactions are revealed to be equivalent to connections between tensile and shear springs. Therefore the present particle method is simple and corresponding physical meaning is clear. In the creep analysis connections among particles are represented by Blackburn model. A tensile 304SS plate with steady load is analyzed. The calculated result is compared with an experimental result and is in good agreement with it. A tensile stainless steel plate with steady strain is analyzed. The stress relaxation with creep strain is compared with experimental results and is in good agreement with it.

Keywords: Particle Method, Creep, LMFBR

1. INTRODUCTION

Development of an evaluation method for creep fatigue life of long time strain hold is important for the structural design of LMFBR (Liquid Metal Fast Breeder Reactor) components. It is difficult to solve creep deformations when large deformed boundaries are involved. The mesh will be distorted and the accuracy is poor when the displacement of the boundaries is large. Meshless methods have been studied to overcome these problems. Besides, more and more complex geometries are required to analyze and mesh generation often takes more time than the structure analysis. Complex grid generation process will be much simplified in meshless methods. The meshless methods which have been developed for structural analysis are DEM (Diffused Element Method) (Nayroles et al., 1992), EFGM (Element Free Galerkin Method) (Belytchko et al., 1994) and FMM (Free Mesh Method) (Yagawa et al., 1996). DEM and EFGM employ moving least-square interpolations which need integral calculations on background cells. FMM is based on FEM (Finite Element Method) though it needs no explicit data of connectivity between nodes. FMM is developed for large scale analysis on parallel computers.

MPS (Moving Particle Semi-implicit) method has been developed for incompressible flow analysis without elements. Moving interface problems, such as wave breaking, vapor explosions and boiling, were successfully analyzed using MPS method (Koshizuka and Oka, 1996, 1998 and 1999). MPS method has also been used for fluid-structural interaction. Chikazawa et al. (1999, 2001) calculated sloshing in an elastic tank which is treated as a thin structure represented by particles

A new particle method for elastic analysis developed using differential operators in MPS particle interaction models (Chikazawa et al., 2001). In the present study, the new elastic particle method is extended to creep analysis.

2. PARTICLE MODEL FOR ELASTIC STRUCTURES

2.1 Governing Equations

Governing equations for two-dimensional isotropic elastic structures are

$$\begin{cases} (\lambda+\mu)\dfrac{\partial}{\partial x}\left(\dfrac{\partial u}{\partial x}+\dfrac{\partial v}{\partial y}\right)+\mu\left(\dfrac{\partial^2 u}{\partial x^2}+\dfrac{\partial^2 u}{\partial y^2}\right)=-f_x \\ (\lambda+\mu)\dfrac{\partial}{\partial y}\left(\dfrac{\partial u}{\partial x}+\dfrac{\partial v}{\partial y}\right)+\mu\left(\dfrac{\partial^2 v}{\partial x^2}+\dfrac{\partial^2 v}{\partial y^2}\right)=-f_y \end{cases} \tag{2-1}$$

where $\vec{u}=(u,v)$ is displacement vector and $\vec{f}=(f_x, f_y)$ is external force vector. λ and μ are constants that are expressed by

$$\lambda=\frac{\theta E}{(1+\theta)(1-\theta)} \tag{2-2}$$

$$\mu=\frac{E}{2(1+\theta)} \tag{2-3}$$

where E is Young's modulus and θ is Poisson's ratio. The governing equations can be reduced to diffusion, rotation and volumetric strain terms.

$$\begin{cases} 2\mu\nabla^2 u+\mu\dfrac{\partial}{\partial y}\left(\dfrac{\partial v}{\partial x}-\dfrac{\partial u}{\partial y}\right)+\lambda\dfrac{\partial}{\partial x}\left(\dfrac{\partial u}{\partial x}+\dfrac{\partial v}{\partial y}\right)=-f_x \\ 2\mu\nabla^2 v+\mu\dfrac{\partial}{\partial x}\left(\dfrac{\partial v}{\partial x}-\dfrac{\partial u}{\partial y}\right)+\lambda\dfrac{\partial}{\partial y}\left(\dfrac{\partial u}{\partial x}+\dfrac{\partial v}{\partial y}\right)=-f_y \end{cases} \tag{2-4}$$

Each particle holds four variables: two components of the displacement vector $\vec{u}=(u,v)$, rotation $R=\nabla\times\vec{u}$ and divergence $D=\nabla\cdot\vec{u}$. Rewriting the equations in the matrix form, we have

$$\begin{pmatrix} 2\mu\nabla^2 & 0 & \mu\dfrac{\partial}{\partial y} & \lambda\dfrac{\partial}{\partial x} \\ 0 & 2\mu\nabla^2 & -\mu\dfrac{\partial}{\partial x} & \lambda\dfrac{\partial}{\partial y} \\ -\dfrac{\partial}{\partial y} & \dfrac{\partial}{\partial x} & -1 & 0 \\ \dfrac{\partial}{\partial x} & \dfrac{\partial}{\partial y} & 0 & -1 \end{pmatrix}\begin{pmatrix} u \\ v \\ R \\ D \end{pmatrix}=\begin{pmatrix} -f_x \\ -f_y \\ 0 \\ 0 \end{pmatrix} \tag{2-5}$$

2.2 Particle Model

A new particle method for elastic structure has been developed by Chikazawa (Chikazawa et. al., 2001). In the method, a particle interaction model of MPS method (Koshizuka and Oka, 1996) is used. In the MPS method, each particle interacts with its neighboring particles using a weighting function (see fig.1).

$$w(r_{ij}) = \begin{cases} \dfrac{r_e}{r_{ij}} - 1 & , r_{ij} \le r_e \\ 0 & , r_{ij} > r_e \end{cases} \tag{2-6}$$

where r_{ij} is the distance between particles i and j, and r_e is the radius of weighting function. The interaction area is limited by r_e. Particle number density at particle i is defined as

$$n_i = \sum_{j \ne i} w(r_{ij}) \tag{2-7}$$

The particle number density is constant at inside particles if the configuration of particles is uniform. This constant value is denoted by n^0. The particle number density decreases on boundaries because there are no particles outside. Interactions between particles are averaged by the weighting function. Suppose f is an arbitrary variable, Laplacian at particle i is modeled as follows

$$\left(\nabla^2 f\right)_i = 2d \sum_{j \ne i} \frac{f_j - f_i}{r_{ij}^2} \frac{w(r_{ij})}{n_i} \tag{2-8}$$

where d is the number of space dimensions. Models for other differential operators, such as divergence, rotation and gradient, are as follows

$$\left(\nabla \cdot \vec{f}\right)_i = d \sum_{j \ne i} \frac{\left(\vec{f}_j - \vec{f}_i\right) \cdot \vec{t}_{ij}}{r_{ij}} \frac{w(r_{ij})}{n_i} \tag{2-9}$$

$$\left(\nabla \times \vec{f}\right)_i = d \sum_{j \ne i} \frac{\left(\vec{f}_j - \vec{f}_i\right) \cdot \vec{s}_{ij}}{r_{ij}} \frac{w(r_{ij})}{n_i} \tag{2-10}$$

$$\left(\nabla f\right)_i = d \sum_{j \ne i} \frac{\left(f_j - f_i\right)}{r_{ij}} \vec{t}_{ij} \frac{w(r_{ij})}{n_i} \tag{2-11}$$

where $\vec{r}_{ij}$ is a position vector from particle i to j. $\vec{t}_{ij}$ is a unit vector parallel to $\vec{r}_{ij}$ and $\vec{s}_{ij}$ is a unit vector perpendicular to $\vec{r}_{ij}$ (Fig. 2). More details of the particle interaction models are explained in a reference (Koshizuka and Oka, 1996). The rotation model (2-10) is newly developed in the present study. In SPH (Smoothed Particle Hydrodynamics) (Gingold and Monaghan, 1982), which was developed for compressible flow analysis, another gradient model has been used.

$$\left(\nabla f\right)_i = d \sum_{j \ne i} \frac{\left(f_j + f_i\right)}{2r_{ij}} \vec{t}_{ij} \frac{w(r_{ij})}{n_i} \tag{2-12}$$

Corresponding to this gradient model, another rotation model is also developed in the present study as

$$\left(\nabla \times \vec{f}\right)_i = d \sum_{j \ne i} \frac{\left(\vec{f}_j + \vec{f}_i\right) \cdot \vec{s}_{ij}}{2r_{ij}} \frac{w(r_{ij})}{n_i} \tag{2-13}$$

Using the above Laplacian model (2-13), the diffusion terms in the government equations of elastic structures are discretized to,

$$\begin{cases} \left(\nabla^2 u\right)_i = \dfrac{2d}{n^0} \displaystyle\sum_{j \neq i} \dfrac{u_j - u_i}{r_{ij}^2} w\left(r_{ij}\right) \\ \left(\nabla^2 v\right)_i = \dfrac{2d}{n^0} \displaystyle\sum_{j \neq i} \dfrac{v_j - v_i}{r_{ij}^2} w\left(r_{ij}\right) \end{cases} \tag{2-14}$$

The interactions are normalized by n^0 in place of n_i to consider boundary conditions. Using eqs. (2-9) and (2-10), divergence and rotation at particle i are expressed respectively as

$$D_i = d \sum_{j \neq i} \frac{\left(\vec{u}_j - \vec{u}_i\right) \cdot \vec{t}_{ij}}{r_{ij}} \frac{w(r_{ij})}{n_i} \tag{2-15}$$

$$R_i = d \sum_{j \neq i} \frac{\left(\vec{u}_j - \vec{u}_i\right) \cdot \vec{s}_{ij}}{r_{ij}} \frac{w(r_{ij})}{n_i} \tag{2-16}$$

The governing equations are transformed to

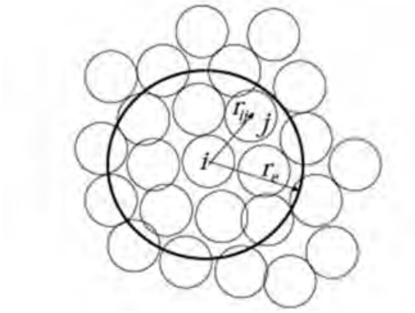
$$\begin{cases} \dfrac{d}{n_0} \displaystyle\sum_{j \neq i} \left\{ 2\mu \dfrac{\left(\vec{u}_j - \vec{u}_i\right) \cdot \vec{t}_{ij}}{r_{ij}^2} t_{ij,x} + 2\mu \dfrac{\left(\vec{u}_j - \vec{u}_i\right) \cdot \vec{s}_{ij}}{r_{ij}^2} s_{ij,x} - 2\mu \dfrac{\left(R_i + R_j\right)/2}{r_{ij}} s_{ij,x} + 2\lambda \dfrac{\left(D_i + D_j\right)/2}{r_{ij}} t_{ij,x} \right\} w\left(r_{ij}\right) = -f_x \\ \dfrac{d}{n_0} \displaystyle\sum_{j \neq i} \left\{ 2\mu \dfrac{\left(\vec{u}_j - \vec{u}_i\right) \cdot \vec{t}_{ij}}{r_{ij}^2} t_{ij,y} + 2\mu \dfrac{\left(\vec{u}_j - \vec{u}_i\right) \cdot \vec{s}_{ij}}{r_{ij}^2} s_{ij,y} - 2\mu \dfrac{\left(R_i + R_j\right)/2}{r_{ij}} s_{ij,y} + 2\lambda \dfrac{\left(D_i + D_j\right)/2}{r_{ij}} t_{ij,y} \right\} w\left(r_{ij}\right) = -f_y \end{cases} \tag{2-17}$$

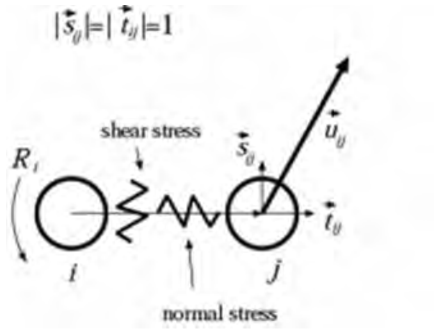
The third terms of the left side represent the volumetric stress components which are determined by gradient of D_i. The gradient model of eq. (2-12) is applied to these terms. The second terms of left side represent removal of rotation from the shear stress components. The rotation model of eq. (2-13) is applied to these terms. The matrix of the left side of eq.(2-5) is completely discretized to eq. (2-17) by the particle interaction models. The matrix equation can be solved by an ordinary solver, for example, SOR method. Displacement of particle j from particle i is $\vec{u}_j - \vec{u}_i$. The displacement vector can be reduced to a perpendicular component $\left(\vec{u}_j - \vec{u}_i\right) \cdot \vec{s}_{ij} \vec{s}_{ij}$ and a parallel component $\left(\vec{u}_j - \vec{u}_i\right) \cdot \vec{t}_{ij} \vec{t}_{ij}$. Equation (2-14) can be rewritten to

$$\begin{cases} \left(\nabla^2 u\right)_i = \dfrac{d}{n_0} \displaystyle\sum_{j \neq i} \left\{ \dfrac{\left(\vec{u}_j - \vec{u}_i\right) \cdot \vec{t}_{ij}}{r_{ij}^2} t_{ij,x} + \dfrac{\left(\vec{u}_j - \vec{u}_i\right) \cdot \vec{s}_{ij}}{r_{ij}^2} s_{ij,x} \right\} w\left(r_{ij}\right) \\ \left(\nabla^2 v\right)_i = \dfrac{d}{n_0} \displaystyle\sum_{j \neq i} \left\{ \dfrac{\left(\vec{u}_j - \vec{u}_i\right) \cdot \vec{t}_{ij}}{r_{ij}^2} t_{ij,y} + \dfrac{\left(\vec{u}_j - \vec{u}_i\right) \cdot \vec{s}_{ij}}{r_{ij}^2} s_{ij,y} \right\} w\left(r_{ij}\right) \end{cases}$$

(2-18)

According to eq. (2-18), two particles behave as if they are connected by two springs: normal and shear springs which are governed by the parallel and perpendicular components of displacement, respectively (Fig. 2).





3. CREEP MODEL

3.1 Steady Creep Model

In the present method, the particle model for elastic structure is extended to creep analysis. The model for steady creep is

$$\dot{\varepsilon}_c = \gamma' \sigma^n = \gamma(\sigma)\sigma \tag{3-1}$$

where ε_c is the creep strain and $\gamma(\sigma)$ is the reciprocal of the viscosity coefficient. In this present method, a visco-plastic model using $\gamma(\sigma)$ which is a function of stress is adapted for creep deformation and stress is assumed to be constant in a time step. Strain between particles i and j is discretized as follows

$$\varepsilon_{c,ij} = \frac{u_{c,j} - u_{c,i}}{r_{ij}} \tag{3-2}$$

where u_c is creep displacement. Equation (3-1) is discretized as follows

$$\frac{\varepsilon_{c,ij} - \varepsilon_{c,ij}^{old}}{dt} = \gamma\sigma \tag{3-3}$$

where $\varepsilon_{c,ij}^{old}$ is the strain at the old timestep. When particles are moved by Lagrangian description, $\varepsilon^{old} = 0$. Equation (3-3) is reduced to

$$\varepsilon_{c,ij} = dt\gamma\sigma \tag{3-4}$$

The equation of elasticity is shown as follows

$$\varepsilon_e = \frac{1}{E}\sigma \tag{3-5}$$

where ε_e is the elastic strain. Comparing Eq.(3-4) to Eq.(3-5), it is suggested that the equation of steady creep deformation must be expressed by the similar equation of elastic deformation substituting E by $E_c = 1/\Delta t\gamma$. The steady creep equation in matrix form is

$$\begin{pmatrix} 2\mu_c\nabla^2 & 0 & \mu_c\dfrac{\partial}{\partial y} & \lambda_c\dfrac{\partial}{\partial x} \\ 0 & 2\mu_c\nabla^2 & -\mu_c\dfrac{\partial}{\partial x} & \lambda_c\dfrac{\partial}{\partial y} \\ -\dfrac{\partial}{\partial y} & \dfrac{\partial}{\partial x} & -1 & 0 \\ \dfrac{\partial}{\partial x} & \dfrac{\partial}{\partial y} & 0 & -1 \end{pmatrix}\begin{pmatrix} u_c \\ v_c \\ R_c \\ D_c \end{pmatrix} = \begin{pmatrix} -f_x \\ -f_y \\ 0 \\ 0 \end{pmatrix} \tag{3-6}$$

$$E_c = \frac{1}{dt\theta} \tag{3-7}$$

$$\lambda_c = \frac{E_c\theta}{(1+\theta)(1-\theta)} \tag{3-8}$$

$$\mu_c = \frac{E_c}{2(1+\theta)} \tag{3-9}$$

where θ is Poisson's ratio. Equation (3-6) can be solved in the particle method used for Eq.(2-5).

3.2 Simple Hardening Model

A simple hardening model used here is shown as follows

$$\dot{\varepsilon}_c = \gamma(\sigma - H\varepsilon) \tag{3-10}$$

where H is the coefficient of hardening. Strain between particles i and j is discretized as follows.

$$\frac{\varepsilon_{c,ij} - \varepsilon_{c,ij}^{old}}{dt} = \gamma\sigma - \gamma H\left(\varepsilon_{c,ij}^{total} + \frac{1}{2}\left(\varepsilon_{c,ij} - \varepsilon_{c,ij}^{old}\right)\right) \tag{3-11}$$

where $\varepsilon_{c,ij}^{old}$ is the strain at the old time step. When particles are moved by Lagrangian description, $\varepsilon^{old} = 0$. Equation (3-3) is reduced to

$$\left(1 + \frac{dt\gamma H}{2}\right)\varepsilon_{c,ij} = dt\gamma\sigma - dt\gamma H\varepsilon_{c,ij}^{total} \tag{3-12}$$

where $\varepsilon_{c,ij}^{total}$ is the total creep strain at the time step. Using the same way for Eq.(3-4), the equations for creep deformation with hardening are expressed as follows

$$\begin{pmatrix} 2\mu_c\nabla^2 & 0 & \mu_c\dfrac{\partial}{\partial y} & \lambda_c\dfrac{\partial}{\partial x} \\ 0 & 2\mu_c\nabla^2 & -\mu_c\dfrac{\partial}{\partial x} & \lambda_c\dfrac{\partial}{\partial y} \\ -\dfrac{\partial}{\partial y} & \dfrac{\partial}{\partial x} & -1 & 0 \\ \dfrac{\partial}{\partial x} & \dfrac{\partial}{\partial y} & 0 & -1 \end{pmatrix}\begin{pmatrix} u_c \\ v_c \\ R_c \\ D_c \end{pmatrix} = \begin{pmatrix} -f_x \\ -f_y \\ 0 \\ 0 \end{pmatrix} - \gamma H\begin{pmatrix} 2\mu_c\nabla^2 & 0 & \mu_c\dfrac{\partial}{\partial y} & \lambda_c\dfrac{\partial}{\partial x} \\ 0 & 2\mu_c\nabla^2 & -\mu_c\dfrac{\partial}{\partial x} & \lambda_c\dfrac{\partial}{\partial y} \end{pmatrix}\begin{pmatrix} u_{c,t} \\ v_{c,t} \\ R_t \\ D_t \end{pmatrix} \tag{3-13}$$

$$E_c = \frac{1}{dt\gamma}\left(1 + \frac{dt\gamma H}{2}\right) \tag{3-14}$$

$$\lambda_c = \frac{E_c\theta}{(1+\theta)(1-\theta)} \tag{3-15}$$

$$\mu_c = \frac{E_c}{2(1+\theta)} \tag{3-16}$$

where $u_{c,t}$, $v_{c,t}$, $R_{c,t}$ and $D_{c,t}$ are the total creep displacement in x direction, in y direction, rotation and divergence respectively. The equation (3-13) can be solved in the particle method used for Eq.(2-5).

3.3 Blackburn Model

Blackburn creep model (Blackburn, 1972) is shown as follows

$$\varepsilon = C_1\left(1 - e^{-r_1 t}\right) + C_2\left(1 - e^{-r_2 t}\right) + \dot{\varepsilon}_m t \tag{3-17}$$

where $C_1, C_2, \dot{\varepsilon}_m, r_1, r_2$ are functions of stress σ (kg/mm^2) and temperature T (deg-C) and were decided by experiments (Yoshitake, et al, 1986).

$$\log_{10}(\alpha_c t_R) = -17.54301 + \frac{26248.54}{T+273.15} - \frac{6104.579}{T+273.15}\log_{10}\sigma - \frac{425.0012}{T+273.15}(\log_{10}\sigma)^2 \tag{3-18}$$

$$\dot{\varepsilon}_m = 62.416\exp\left[-\frac{40812}{8.31(T+273.15)}\right]t_R^{-1.1335} \tag{3-19}$$

$$C_1 = 1.2692\frac{\dot{\varepsilon}_m^{0.74491}}{r_1} \tag{3-20}$$

$$C_2 = 0.48449\frac{\dot{\varepsilon}_m^{0.81155}}{r_2} \tag{3-21}$$

$$r_1 = 103.37 t_R^{-0.72607} \tag{3-22}$$

$$r_2 = 17.255 t_R^{-0.86775} \tag{3-23}$$

where α_c is a parameter which express experimental uncertainty. $\alpha_c = 1$ means the best estimation of creep strain and all experimental results performed were covered in the range $0.1 \le \alpha_c \le 10$ In this study, the best estimation $\alpha_c = 1$ is used. The analytical solution of Eq.(3-10) is expressed as follows

$$\varepsilon = \frac{\sigma}{H}\left(1 - e^{-\gamma H t}\right) \tag{3-24}$$

Comparing Eq.(3-24) with Eq.(3-17), the first and second terms of the right hand side of Eq.(3-24) are the same as Eq.(3-17). The first and second terms can be modeled by the simple hardening model expressed by Eq.(3-10). The third term of Eq.(3-24) is steady creep model which can be expressed by Eq.(3-1). Finally, creep curve of 304SS Eq.(3-17) is modeled by the three springs expressed as follows

$$\varepsilon = \varepsilon_1 + \varepsilon_2 + \varepsilon_3 \tag{3-25}$$

$$\dot{\varepsilon}_1 = \gamma_1(\sigma - H_1\varepsilon_1) \quad (3\text{-}26)$$

$$\dot{\varepsilon}_2 = \gamma_2(\sigma - H_2\varepsilon_2) \quad (3\text{-}27)$$

$$\dot{\varepsilon}_3 = \gamma_3\sigma \quad (2\text{-}28)$$

Equation (3-26) and Eq.(3-27) can be solved independently by the methods for Eq.(3-10) and Eq.(3-1) respectively.

4. RESULT

4.1 304SS Creep Plate

The calculation result of a high temperature tensile 304SS palte is compared with an experiment. The calculation geometry is shown in Fig. 3. Material of the plate is 304SS stainless steel and temperature is 650deg-C. The length and width of the plate are 10.0 and 5.0cm, respectively. The plate is fixed at the top and loaded uniformly 88.263MPa at the bottom. Figure 4 is the calculated stain of the plate. The figure also shows the result of an creep strain experiment performed in the same condition (Asayama, T. and Kawakami, T., 1999). The calculated result is in good agreement with the experimental result.

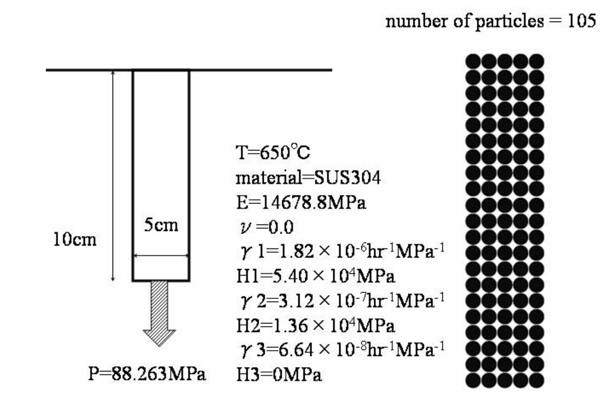


Fig.3 Geometry of 304SS Creep Calculation

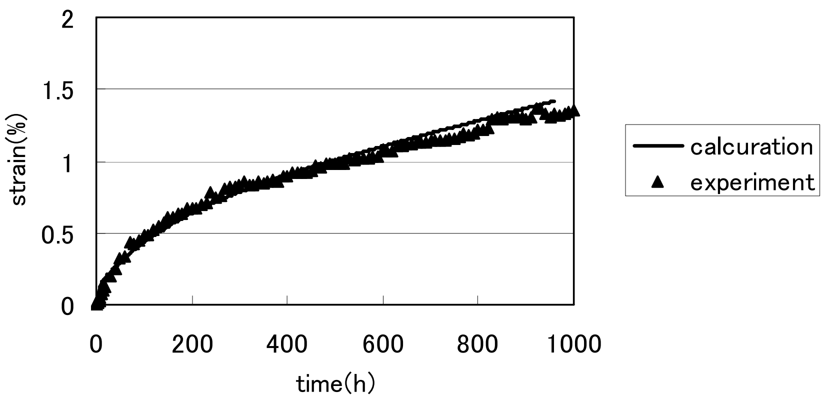


Fig.4 Result of 304SS Creep Calculation

4.2 304SS Creep Relaxation

Stress relaxation in steady strain is important in creep analysis. The result of stress relaxation analysis is compared with an experiment. The calculation geometry is shown in Fig. 5. Material of the plate is 304 stainless steel and the temperature is 600deg-C. The length and width of the plate are 10.0 and 5.0cm, respectively. The plate is fixed at the top and the put primary load of 104MPa in the first time step. Then the end of the plate is fixed and relaxation is started. The primary elastic displacement is calculated and the total elastic and creep displacements are maintained constant in the all time steps. Yong's modulus is 148919MPa. Figure 6 is the calculated elastic and creep strain of the plate. The creep strain increases and the elastic strain decreases in the condition of total strain is kept constant. Figure 7 is the calculated stress compared with the experimental result in the same condition (Asayama, T, 1999). The result is in good agreement with analytical one.

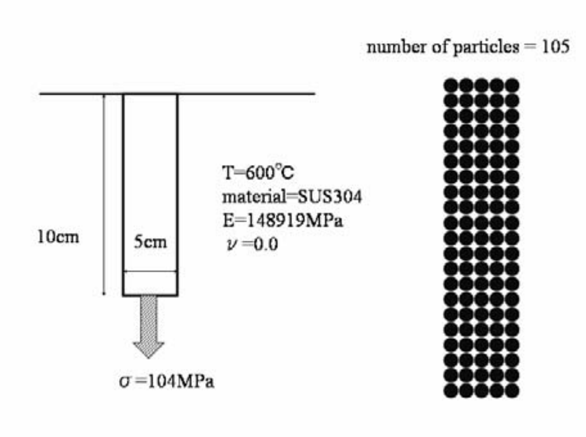


Fig.5 Geometry of 304SS Relaxation Calculation

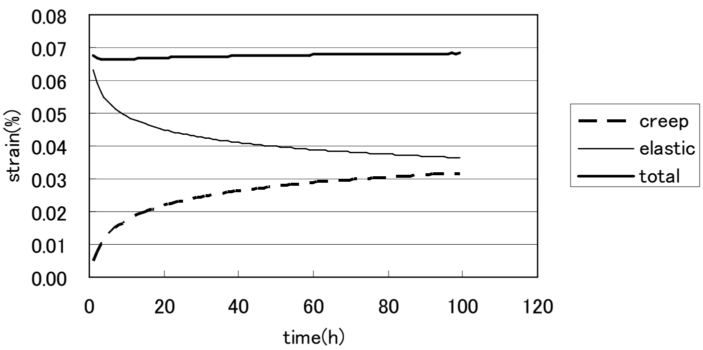


Fig.6 Calculated Strain of 304SS Relaxation

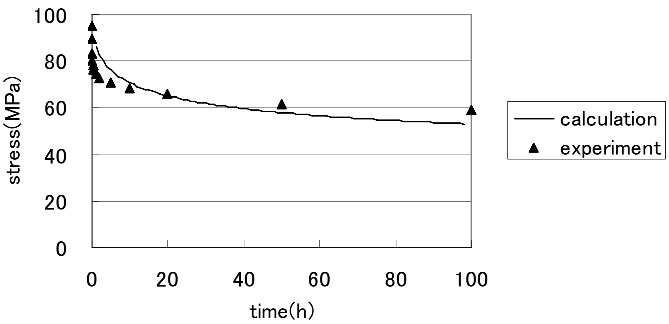


Fig.7 Calculated Stress of 304SS Relaxation

5. CONCLUSIONS

A new particle method for elastic and creep analysis is developed. In this method, no element is used and particle interactions are modeled by the same way as MPS method which was developed for fluid flow analysis. Particles behave as if they are connected by tensile and shear springs. A model for creep deformation is represented to replace these elastic springs into creep ones using Blackburn model. A tensile 304SS plate with steady load is calculated. The result is compared with analytical and experimental results and is in good agreement with them. A tensile stainless steel plate with steady strain is analyzed. The stress relaxation with creep strain is compared with experimental results and is in good agreement with it.

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