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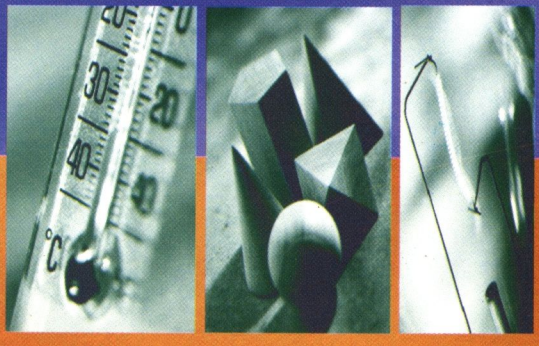

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JILID I: SAINS TEKNOLOGI

NUMERICAL ANALYSIS OF METAL POWDER UNDER LOADING

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Abstract: The coupled mechanical and thermal analysis of powder during the warm compaction process has been studied. This paper presents the development of the finite element model for the simulation of warm metal powder compaction process. In the modelling, the behaviour of powder is assumed to be rate independent thermo-elastoplastic material. The material constitutive laws are derived based on a continuum mechanics approach. The deformation process has been described by a large displacement based finite element formulation. Three constitutive relations namely Mohr-Coulomb yield model, Elliptical Cap yield model, and the combination of these two have been used to describe the deformation behaviour of the powder mass during the compaction process. These yield models were tested, however an Elliptical Cap model was shown to be the most appropriate to represent the compaction process. The staggered-incremental-iterative solution strategy has been established to solve the non-linearity in the systems of equations. The numerical simulation results were validated against the experimental data, where a good agreement was found between the numerical simulation results and the experimental data.

Keywords: Warm compaction, Finite element method, Continuum mechanics, Thermo-elastoplastic material model

INTRODUCTION

The production of solid component from porous materials by compacting and sintering has been in existence since early nineteen hundreds as a new generation of manufacturing process. In the last three decades, a wide range of structural components especially for automotive industry has been developed for production using this method [1]. The development of manufacturing industry in Malaysia provides greater market opportunities of this type of process. Statistics show the production of mechanical components, using porous materials forming technology, in 1999 is 4.1 kt in Malaysia compared to 83.4 kt in Japan [2]. In order to expand the market and give lowest total cost, efforts to improve this technology have focused on ways to enhance the mechanical properties and tolerances of the finished parts. A major advance in this technology has been the warm forming process, which can utilize traditional powder forming equipment. This method is applicable to most porous material/powder systems but requires that both the porous material and the die assembly are heated up to a temperature in the range of 100-150 °C. The temperature range 100-150 °C roughly delimits the working temperature because at the temperature above 150 °C, lubricants begin to break down, and at the higher temperature iron powder oxidizes more rapidly. However, at temperature below about 100 °C, sufficient loading effect cannot be achieved. The process can produce components having good surface finish and dimensional tolerance such that minimal further processing is required, therefore relatively less time is taken to produce a specific component.

There is wide agreement in the industry that the major source of any physical flaw in a product arises from an inhomogoneous density distribution within the compact and internal cracks initiated on an internal shear plane. The density distribution depends on the combination of many factors such as geometrical shape, mechanical properties of the materials to be compacted, powder-tool frictional behaviour and the pressing cycle. An analysis of the of warm forming process is necessary to improve and to get a deeper understanding about the effects of process variables on the product. The optimization of process variables may be achieved by a time consuming trial-and-error procedure or tooling development programme, which is expensive. Furthermore, it is relatively difficult to predict the porous materials forming behaviour experimentally [3,4].It becomes clear from the description above that the analysis of warm forming process is important because the compact green density influences the performance of the final part. The variations of green density will also cause shape

distortion after sintering along with regions of elevated stress and stress concentrations [5]. In this paper, a finite element model is developed to predict the stress, density and flow of powder mass during the warm forming process and the numerical simulation results were validated against the experimental data.

MATERIAL AND METHODS

Finite Element Implementation

In practical design and analysis, the most important steps are the proper idealization of the actual problem and the correct interpretation of the result. Considerable knowledge regarding the characteristics of the system and its mechanical behaviour are required in establishing an appropriate idealization depending on the complexity of the actual system to be analysed. In order to construct the numerical solution algorithm of a continuum problem, it is basically necessary to establish the algebraic equations that govern the response of the system. A most important formulation approach, which is widely used for the establishment of solution algorithm for practical problems is the displacement based finite element method [6]. During the powder compaction process, the material domain transforms from loose powder state to solid state due to densification. Therefore, the formulation must capture both these states of deformation. The starting point for this formulation is the principle of virtual work [7]. This principle arises from consideration of a body subjected to two entirely unrelated loading states. Under the application of some external loads, internal stresses are generated which result in equilibrium conditions being satisfied.

The virtual work done by the internal force should be equivalent to the virtual work done by the external force. In powder compaction process, the external applied force to the powder mass must be balanced by the internal reaction of the powder. Therefore, the relationship between internal and external virtual works can be expressed as

$$\underbrace{\int_{\Omega} \sigma \delta \varepsilon d\Omega}_{\text{internal}} = \underbrace{\int_{\Omega} \rho \mathbf{b} \delta \mathbf{u} d\Omega + \int_{\Gamma_t} \mathbf{t} \delta \mathbf{u} d\Gamma_t}_{\text{external}} \qquad (1)$$

where $\delta \mathbf{u}$ is the virtual displacement, ρ is the mass density, $\mathbf{b}$ and $\mathbf{t}$ are the body force and traction, respectively. For the purpose of finite element discretization, six-noded isoparametric triangular elements are used due to its ability to estimate any shape of boundary. The domain is discretized into a finite number of elements and the relating equation is

$$\Omega = \sum_{e=1}^{n} \Omega_e \qquad (2)$$

where Ω is the whole domain and n is the number of elements. The displacement, u_i and strain, ε_i at any point within an element can be expressed as

$$u_i = \sum_{i=1}^{6} N_i a_i \quad \text{and} \quad \varepsilon_i = \sum_{i=1}^{6} \mathbf{B}_i a_i \qquad (3)$$

where a_i is the virtual displacement, N_i is the shape function and $\mathbf{B}_i$ is the discrete strain operator. Considering the non-linear material behaviour and including the residual element vector $\mathbf{r}^e$, equation (1) becomes

$$\int_{\Omega} \sigma \delta \varepsilon d\Omega - \int_{\Omega} \rho \mathbf{b} \delta \mathbf{a} d\Omega - \int_{\Gamma} \mathbf{t} \delta \mathbf{a} d\Gamma_t = \mathbf{r}^e \qquad (4)$$

By introducing the thermo-elastoplastic relationship [8] and ε from equation (3), equation (4) can be written as

$$\int_{\Omega} \mathbf{D}_{ep}(\mathbf{Ba} - XT)\delta\varepsilon d\Omega - \int_{\Omega} \rho \mathbf{b}\delta\mathbf{a} d\Omega - \int_{\Gamma} \mathbf{t}\delta\mathbf{a} d\Gamma_t = \mathbf{r}^e \tag{5}$$

or

$$\int_{\Omega} \mathbf{D}_{ep}\mathbf{Ba} d\Omega - \int_{\Omega} \mathbf{D}_{ep} XT d\Omega - \int_{\Omega} \rho N_e^T \mathbf{b} d\Omega - \int_{\Gamma} N_e^T \mathbf{t} d\Gamma_t = \mathbf{r}^e \tag{6}$$

or

$$\int_{\Omega} \mathbf{B}_e^T \mathbf{D}_{ep}\mathbf{B}_e \mathbf{a} d\Omega - \int_{\Omega} \mathbf{D}_{ep} XT d\Omega - \left[\int_{\Omega} \rho N_e^T \mathbf{b} d\Omega + \int_{\Gamma} N_e^T \mathbf{t} d\Gamma_t \right] = \mathbf{r}^e \tag{7}$$

Equation (7) can be written in linear form as

$$\left[\int_{\Omega_e} \mathbf{B}_e^T \frac{\partial \sigma}{\partial \varepsilon} \mathbf{B}_e d\Omega - \int_{\Omega_e} \mathbf{B}_e^T \frac{\partial \sigma}{\partial \varepsilon} XT d\Omega \right] \{\Delta \mathbf{a}_e\} = \{\mathbf{r}^e \tag{8}$$

or

$$[\mathbf{K}_e]\{\Delta \mathbf{a}_e\} = \{\mathbf{r}^e \tag{9}$$

where $[\mathbf{K}]$ is the tangential stiffness matrix, $\{\Delta \mathbf{a}\}$ is the prescribed incremental displacement at the boundary condition or the unknown incremental nodal displacement vector and $\{\mathbf{r}\}$ is the force vector including the body force. The elastoplastic tangent modulus is set as

$$\frac{\partial \sigma}{\partial \varepsilon} \begin{cases} = \mathbf{D}_e & \text{if} \quad F < 0 \\ = \mathbf{D}_{ep} & \text{if} \quad F = 0 \end{cases} \tag{10}$$

The global stiffness matrix, $[\mathbf{K}]$ and force vector, $\{\mathbf{R}$ can be written as

$$[\mathbf{K}] = \sum_{e=1}^{n} \mathbf{K}_e \quad \text{and} \quad \{\mathbf{R}\} = \sum_{e=1}^{n} \mathbf{r}^e \tag{11}$$

where n is the total number of element. Therefore, the global displacement equation becomes

$$[\mathbf{K}]\{\Delta \mathbf{a}\} = -\{\mathbf{R}\} \tag{12}$$

Solution Procedure

The thermo-elastoplastic constitutive laws lead to the equation (12) become non-linear. Therefore, it cannot be solved directly, and requires an incremental iterative technique. An approximate solution can be obtained using an updated Lagrangian strategy where all the variables must be referred to the previously calculated equilibrium configurations. In order to complete the solution procedure for the deformation of powder mass, a staggered-incremental-iterative solution procedure is applied. The total prescribed displacement is divided into n-numbers of small increments where each increment requires an iterative procedure to obtain its solution. The coupled thermo-mechanical computational flowchart using staggered-incremental-iterative solution procedure can be seen in Figure 1.

RESULTS AND DISCUSSIONS

The numerical simulation of warm metal powder compaction process has been modelled to generate a green compact of simple plain bush component. Since a displacement based formulation is adopted, the implementation of loading in the finite element code is achieved by the use of prescribed nodal displacements. The direction of this displacement is always in a vertical plane, which represents the axial punch load. A fill depth of 20 mm was used where the mesh consists of 38 elements and 101 nodes represent the powder material domain whereas 20 elements and 84 nodes represent the interface. The movements of the top punch were divided into 20 steps to give a 50% height reduction of the original fill depth. In order to represent the Updated Lagrangian strategy, the nodal coordinates, stresses, strains and densities were updated at each time step.

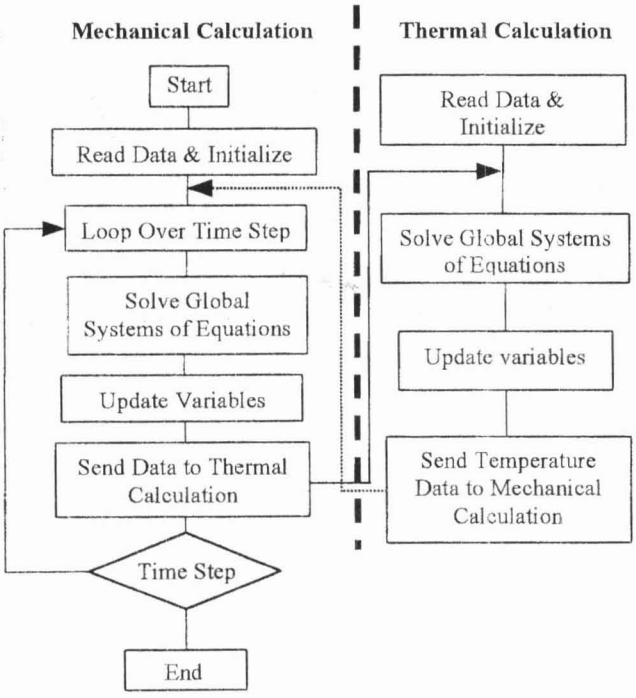

Figure 1 Summary of Complete Computational Procedure

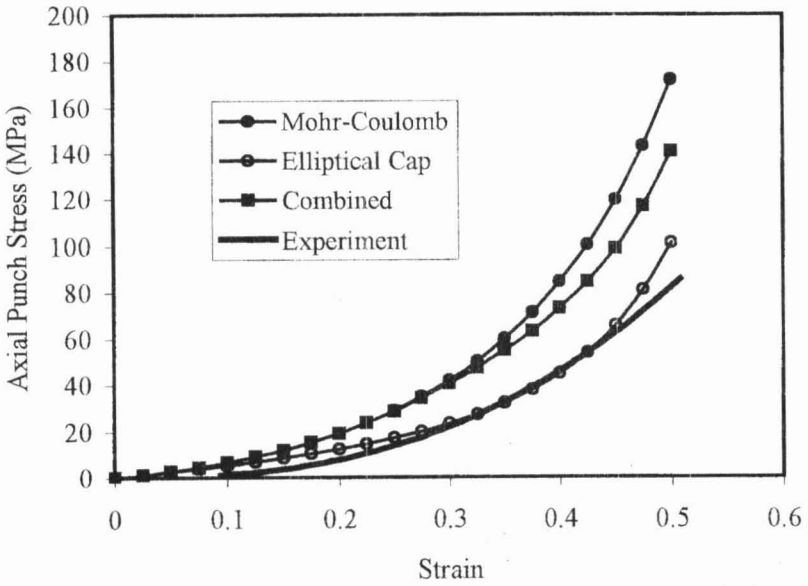

Figure 2: Force Balance for Different Yield Models

Figure 2 shows the force-balance results presented as stress-strain curves where the three yield models are compared with the experimental data. In general, these three models show similar trend with respect to stress development against strain. However, the stress level predicted is different for each model. The Mohr-Coulomb yield model produces the higher stress compared to Elliptical Cap model. In Elliptical Cap yield model, there is a critical state line which limits the elastic and inelastic deformations. No stress state should be above this critical state line. Any stress state inside the yield surface in Mohr-Coulomb yield model may be above the critical state line in Elliptical Cap yield model. Hence the stress predicted by Elliptical Cap yield model is lower than that of Mohr-Coulomb yield model. The close agreement with experimental data is achieved by the Elliptical Cap yield model.

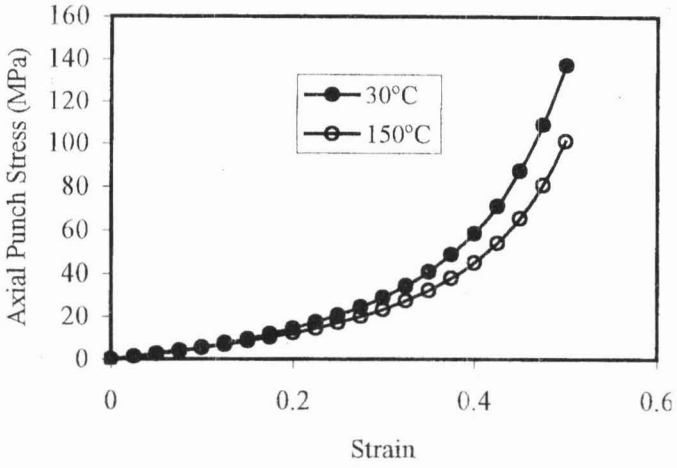

Figure 3: Compaction Force Balance

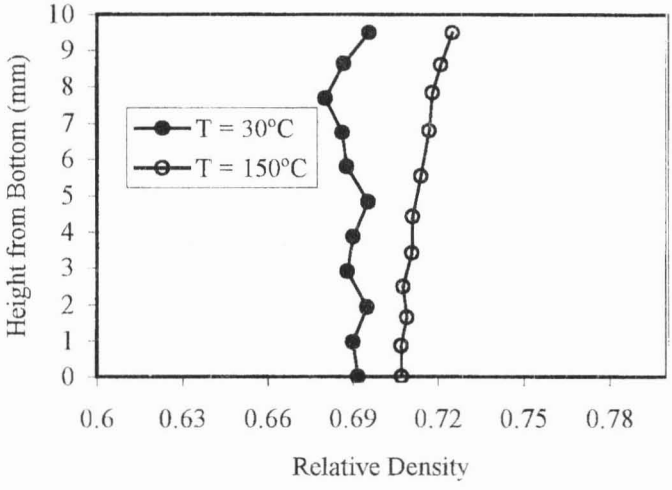

Figure 4: Green Density Variation at Different Temperature

Figure 3 illustrates the axial stress with respect to compaction strain for the compaction at room temperature and elevated temperature. The compaction at elevated temperature produces a lower stress compared to the compaction at room temperature. This is caused the shrinkage of yield surface due to heating up the powder mass prior to compaction. The physical meaning of this phenomenon is that in warm compaction process, a considerable lower force is required to obtain a specific displacement. The variation of density within the powder compact after the compaction phase has been depicted in Figure 4. It is evident from Figure 4 that the density distribution is more uniform in the compact generated through warm compaction process. This is also consistent with the previous explanation that

warm compaction process can produce a part with more uniform density distribution compared to conventional cold compaction process.

CONCLUSION

A numerical analysis of metal powder under mechanical together with thermal load was analysed. Three yield models were used to represent the deformation behaviour of powder mass during the warm forming process. The results are compared with the warm compaction experimental data. An Elliptical Cap yield model is suitable to represent the behaviour of warm metal powder mass during the compaction process. The warm compaction model produces the more uniform density distribution.

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REFERENCES

1. Whittaker, D. 1990. Powder metallurgy applications in the automotive industry. *Proc. World Conference on Powder Metallurgy PM 90.* pp. 109-116

2. Fujiwara, Y. 2000. The present and future of powder metallurgy in Asia and Oceania. *Proc. 2000 Powder Metallurgy World Congress PM 2000.* pp. XXXII-XLIV

3. Nakagawa, T. & Masaaki, S. 1992. Simulation of powder densification in die compaction process. *Advances in Powder Metallurgy and Particulate Materials.* **2**: 43-57

4. Bouvard, D. & McMeeking, M. 1996. Estimation of the densification kinetics of particle aggregates through the simulation of the deformation of an average interparticle neck. In German, R. M., Messing, G. L. & Cornwall, R. G. (eds.). *Sintering Technology.* pp. 37-44. New York: Marcel Dekker, Inc.

5. Häggblad, H.-Å. & McEwan, K. 1992. Explicit versus implicit finite element simulation of metal powder compaction. In Chenot, Woods & Zienkiewicz (eds.). *Numerical Methods in Industrial Forming Processes.* pp. 875-881. Balkema Rotterdam: Springer-Verlag.

6. Bathe, J. K. 1982. *Finite element procedures in engineering analysis.* New Jersey: Prentice-Hall Inc.

7. Zienkiewicz, O. C. & Taylor, R. L. 1989. *The finite element method.* United Kingdom: McGraw-Hill Book Company.

8. Rahman, M. M., Ariffin, A. K. & Anuar, A. 2002. Finite element method for the analysis of warm metal powder compaction process.*Proc. 2nd World Engineering Congress. Manufacturing Engineering Automation & Robotics. Pp. 258-262*