Journal of Achievements in Materials and Manufacturing Engineering
VOLUME 24
ISSUE 1
September
2007

Research activities of computer-aided materials processing laboratory

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Received 07.03.2007; published in revised form 01.09.2007

Analysis and modelling

ABSTRACT

Purpose: of this paper is to review the research works carried out at the national research laboratory for computer-aided materials processing at the department of mechanical engineering at KAIST.
Design/Methodology/approach: The research papers published so far from the laboratory were carefully reviewed and highlights for developing simulation tools for mesh generation, 2D or 3D finite element analyses for forging, shape rolling, solidification, semi-solid forging, compression molding of thermoset composites, injection molding without or with short fibers, and expert system for multi-stage axi-symmetric cold forging, extrusion, and multi-pass shape rolling are recaptured.
Findings: According to this survey, the important issues involved with program developments and their industrial applications were revisited.
Research limitations/implications: Understanding of material behaviour at various processing conditions and characterization of proper boundary conditions in terms of friction and temperature should be carefully made. Handling of complex geometry and computational efficiency for such geometry should be improved as well. Further development of three dimensional design systems should be necessary.
Practical implications: Proper usage of the simulation tools and interface such tools with the automatic design system with the help of artificial intelligence will be very useful at the design stage of new manufacturing products and processes. In addition, proper understanding of deformation mechanics is of importance to properly utilize such numerical tools.
Originality/value: Various aspects of limitations involved with program developments and their usage are identified and some important industrial applications demonstrated.
Keywords: Numerical techniques; Computational material science and mechanics; Plastic forming; Heat treatment

1. Introduction

Recent international market demands that mechanical parts should be produced to net-shape or near net-shape with improved mechanical properties, smooth surface finish, good dimensional accuracy, material savings, and environmentally friendliness, depending on service requirements. In practice, manufacturing engineers are facing the problem of determining proper materials and design of dies and tools to transform an initial simple billet into more complex product geometries without causing any defects at a lower manufacturing cost, depending on the material, the part geometry, and the process.

Since the decision made at the process and product design levels has a profound effect on the dies and tools design, manufacturing, maintenance, mechanical properties and tool life cycle, a great deal of investigations is being made to reduce an experience-based process development in industry. According to recent remarkable advances in computer technology, the application of computers in manufacturing has been growing rapidly and independently in the area of computer-aided design / computer-aided manufacturing, computer-aided engineering, computer-aided process planning and rapid prototyping to aid design and manufacturing activities in present-day industry.

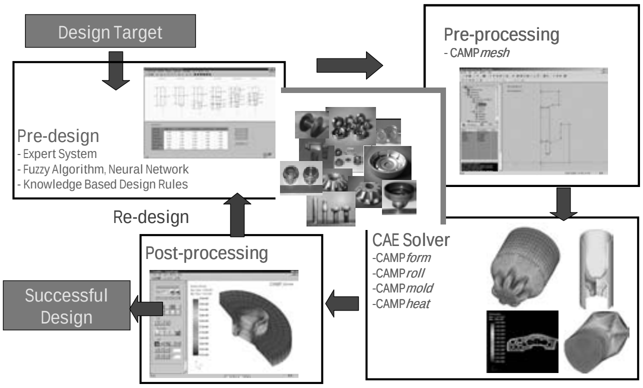


Fig. 1. Overview of the target oriented process design

It is widely known that the analysis of the forming processes is not easy to achieve because of complexity of the problem, especially identification of the boundary conditions. Compared to the conventional slab method, lower and upper bounding techniques, and slip line theory, the finite element (FE) technique is widely accepted since 1970s because of accuracy of the solution. Thus, research activities at national research laboratory for computer-aided materials processing on finite element forming simulations will be reviewed in this paper.

At the present research laboratory, research works for making the design system for product and process development were mainly focused from the beginning since the numerical simulation tools have been developed independently. Thus, there is a necessity of bridging these tools with the design system and verifying the developed system for real usage. This concept is well described in Fig. 1 as a target oriented design process. In this figure, the FE analysis program was coupled with the design system supported by expert system based on knowledge or artificial intelligence technique to determine the better product and process design.

As one of industrial applications of such activities, computer-aided design systems for multi-stage cold forming of fasteners or shafts, three-dimensional extrusion process to manufacture gears, roll pass and profile design in bar rolling, and flat-die hot extrusion process were developed with the help of finite element analyses. Since the identification of proper boundary conditions is the key issue for guaranteeing simulation results, the friction condition and interface heat transfer coefficient were measured by tip test and ring test, respectively. The frictional effect on the equal angular extrusion process was carefully investigated. A multi-pass roll design system to obtain better mechanical properties was introduced as well. In metal forming industry, tool life prediction is another important field of research. In order to investigate tool life of forming dies, elastic analyses were made in couple with the rigid thermo-viscoplastic simulation of deformation. In result, a rather simple correlation between the material property and tool life was obtained. The microstructure evolution during deformation and phase transformation after deformation were analyzed in order to efficiently control the mechanical properties of the billet during heat treatment after deformation. Some simulation results were compared with the experimental findings and the results available in references. Finally, other research works carried out so far at the laboratory will be briefly introduced.

2. Finite element formulation

The rigid-thermo-viscoplastic FE approach proposed by Lee and Kobayashi [1] has been used widely in the field of metal forming analyses. This approach is essentially a coupled procedure to solve equilibrium and energy equations in a staggered manner, in which a rigid-thermo-viscoplastic constitutive model with von Mises yield criterion was used by neglecting the body and inertia forces.

Equilibrium equation: $\sigma_{ij,j} = 0$ in V (1)

Energy equation: $kT_{,ii} - \tilde{\rho} C_p \dot{T} + \dot{r} = 0$ (2)

Constitutive equation: $\sigma'_{ij} = 2\mu\dot{\varepsilon}_{ij}, \ \mu = \dfrac{\bar{\sigma}}{3\dot{\bar{\varepsilon}}}$ (3)

Yield criterion:

$$\bar{\sigma}(\bar{\varepsilon}, \dot{\bar{\varepsilon}}, T) = \sqrt{\frac{3}{2}\sigma'_{ij}\sigma'_{ij}}\ , \dot{\bar{\varepsilon}} = \sqrt{\frac{2}{3}\dot{\varepsilon}_{ij}\dot{\varepsilon}_{ij}} \quad (4)$$

Compatibility equation: $\dot{\varepsilon}_{ij} = \dfrac{1}{2}(v_{i,j} + v_{j,i})$ (5)

Incompressibility: $\dot{\varepsilon}_{kk} = 0$ (6)

Boundary conditions:

$v_i = v_i^*$ on S_U (7)

$\sigma_{ij} n_j = t_i^*$ on S_F (8)

$T = T^*$ on S_T (9)

$q_n = q_n^* = -k\dfrac{\partial T}{\partial n}$ on S_Q (10)

Here, σ_{ij}, σ'_{ij}, and $\bar{\sigma}$ represent the stress tensor, deviatoric stress tensor and effective stress in that order. $\dot{\varepsilon}_{ij}$, $\dot{\bar{\varepsilon}}$, and $\bar{\varepsilon}$ are the rate of deformation tensor, effective strain rate and effective strain in that order as well. S_U and S_F represent the regions where velocity and traction boundary conditions are prescribed, respectively. As part of the traction boundary conditions, the interfacial friction condition was applied on the boundary, S_C. T, k, $\tilde{\rho}$, C_p in Eqn. (2) are the temperature, conductivity, density, and specific heat of the material in that order. $\dot{r}$ is the heat generation rate due to deformation of the workpiece and frictional heat generation between the workpiece and dies. The temperature and heat flux boundary conditions were prescribed on S_T and S_Q, respectively. q_n represents the heat flux between the workpiece and dies and n indicates the outward normal direction at the interfacial surface. The thermal properties are dependent on the temperature in the simulation program.

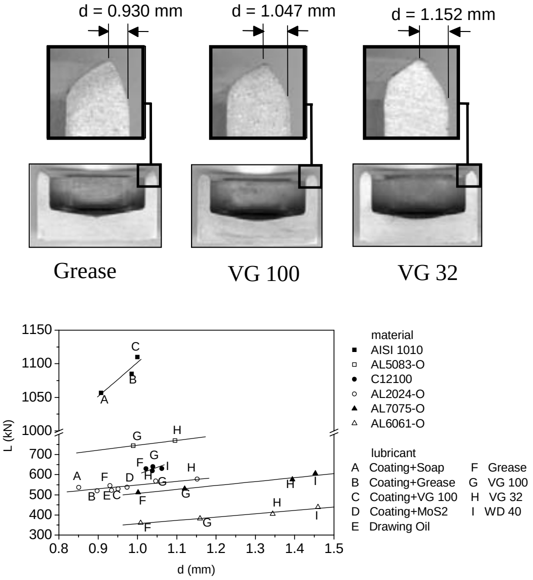


Fig. 2. (a) Photos showing the change in the radial tip distance d and (b) plots of maximum forming load L vs. radial tip distance d obtained from experiments with various materials and lubricants [11]

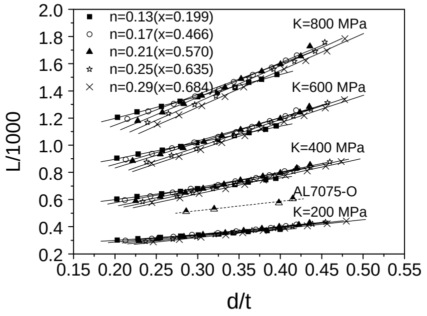


Fig. 3. Graph of L/1000 vs. d/t plots for determining material property [11]

The constant shear friction model described in Eqn. (11) was used to apply the frictional force at the interface between the workpiece and dies:

$$t_i^* = -m_f k_s \frac{2}{\pi}\frac{(\mathbf{v}_r)_i}{\|\mathbf{v}_r\|}\tan^{-1}\left(\frac{\|\mathbf{v}_r\|}{\psi}\right) \quad \text{on } S_C \qquad (11)$$

where m_f and k_s represent the shear friction factor and shear yield strength of the material, respectively and v_r is the relative velocity between the workpiece and dies. In the present study, $\psi = 0.05$ was used for simulations.

For non-isothermal simulations the interface heat transfer coefficient between the workpiece and dies should be determined. For this, ring test was utilized in the work by Burte, et al. [2] and Im [3].

To simulate the porosity distribution in powder metallurgy at room and elevated temperatures, the yield function with compressibility effect was introduced in the work of Im and Kobayashi [4-6]. Oh and Im [7] had investigated the residual porosity distribution in the cold extrusion of the sintered specimen of pure iron powder.

3. Tip test for friction measurement

It is well known that reliability of FE simulations depends on accurate material characterization and description of friction conditions, which govern material flow, forming load, die life, etc. For this reason, Im, et al. [8-10] and Kang, et al. [11] proposed the ‘tip test’ in which a radial tip was formed on the extruded end of the workpiece to simply measure the friction level and material property.

Fig. 2(a) shows the radial tip distance d depending on the lubricants used in experiments made of Al alloys, copper, and carbon steel. Also it was found out experimentally as shown in Fig. 2(b) that the linear relationship between the maximum forming load L and radial tip distance d measured at the stroke of 8.0 mm was maintained regardless of the materials investigated. From the comparison of this linear relationship between the two obtained from the FE simulations and experiments, it was also revealed that the magnitude of the friction at the punch interface m_{fp} was always higher than that at the die interface and that this ratio of shear friction factors increased logarithmically with the level of strain-hardening of the material at room temperature. Its value can be easily determined by the following non-dimensional equation:

$$m_{fp} = 4.37 \times d/t - 0.94 \qquad (12)$$

Here, t represents the thickness of extruded part of the workpiece deformed.

Finally, material property measurement decoupled with the friction effect can be made by putting the non-dimensionalized L/1000 and d/t values obtained from experiments into the graph calibrated with the tip test as shown in Fig. 3.

4. FE program development and mesh generation

In order to handle complex die geometry involved with three-dimensional forming analyses, the geometry modeling of complex die surfaces and the contact treatment algorithm at the dies and workpiece interface are very important. Thus, Kim and Im [12,13] have used Ferguson surface patches for surface modeling and Jacobian inversion and line-surface intersection algorithms for contact treatment algorithm, respectively. They developed the non-isothermal simulation program for the multi-stage bar rolling of carbon steel (CAMP*roll*) at non-steady state and steady state and CAMP*form*-3D.

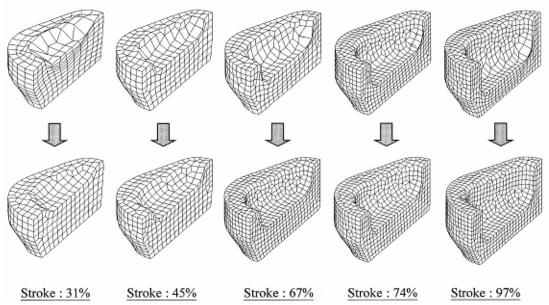


Fig. 4. Grid deformation before and after remeshing at different deformation stages [15]

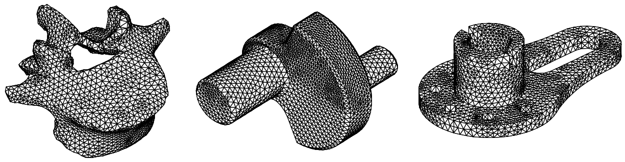

(a) (b) (c)

Fig. 5. Tetrahedral mesh generation of (a) lumbar, (b) crankshaft and (c) slot

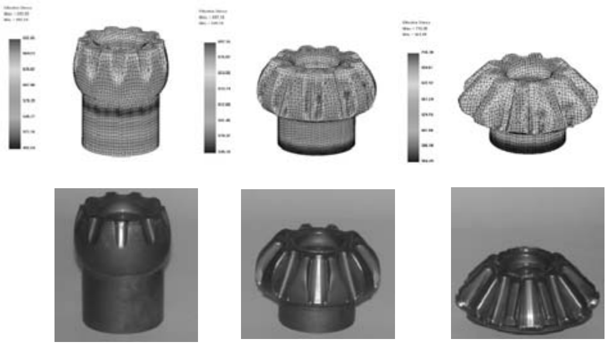


Fig. 6. Comparison of the deformed shapes at the various strokes obtained from bevel gear forging simulations and experiments using carbon steel AISI 1010

One of the prominent features in metal forming simulations using the FE method is the trace of constantly changing shape of the deforming workpiece. However, this leads to a computational error caused by the severe distortion of elements during deformation stage and in extreme cases can prohibit further analyses from being continued. Therefore, adaptive mesh generation might be necessary to finish the three-dimensional analyses economically.

Fig. 4 demonstrates the benchmark test simulation using hexahedral mesh systems generated by a three-dimensional mesh generator developed by Kwak, et al. [14,15].

Even though the hexahedral mesh system provides the accurate solutions, the mesh generation with hexahedral elements for the complex domain with the sharp corner was not so easy. Thus, a tetrahedral mesh generator has been developed by Choi, et al. [16,17] and Son and Im [18] as well and tested with complex geometries as shown in Fig. 5.

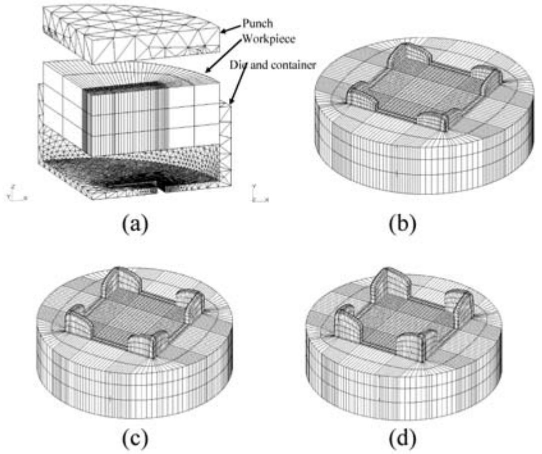
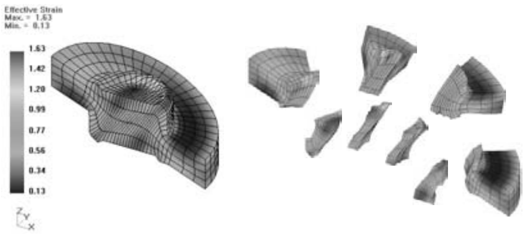


Fig. 7. (a) Initial configuration of L-section die with four holes and deformed shape of the workpiece at various strokes: (b) 0.56 mm (c) 0.84 mm and (d) 1.16 mm [20]



(a) (b)

Fig. 8. (a) Sequential and (b) parallel simulation results of effective strain distribution for swash plate forging [22]

5. Numerical applications

Bevel gear forging simulations were also carried out to investigate the performance of the developed metal forming FE program (CAMP*form*-3D) using hexahedral and tetrahedral mesh generators (CAMP*mesh*). Fig. 6 shows the deformation process obtained from simulations and experiments. As can be seen in this figure, deformed shapes between the two results were very similar and the quality of the generated mesh was very good.

Flat-die extrusion is a squeezing process that compresses an initial billet into a container at elevated temperatures to produce long parts with constant cross- sections. Lee, et al. [19] and Lee and Im [20] simulated the flat-die hot extrusion process at the non-steady state to investigate the effect of bearing length on the extruded shape of the workpiece. Fig. 7 shows an example of the flat-die hot extrusion showing the initial configuration of the L-section die with four holes and the deformed shapes at the various strokes. It is clearly shown in this figure that the workpiece exited the die without having much deflection when applied the designed bearing length.

In the three-dimensional FE analysis of forging processes, a large number of elements are needed for improvement of the solution accuracy. This results in increased computation time and memory requirement, which are still one of major problems for effective usage of three-dimensional metal forming analyses in industry. Thus, Kim and Im [21] and Cheon, et al. [22] applied the parallel computation algorithm in the rigid-viscoplastic FE approach in order to increase the computational efficiency. Fig. 8 shows the distribution of effective strain in the workpiece for sequential and parallel solutions using the sub-domain approach used.

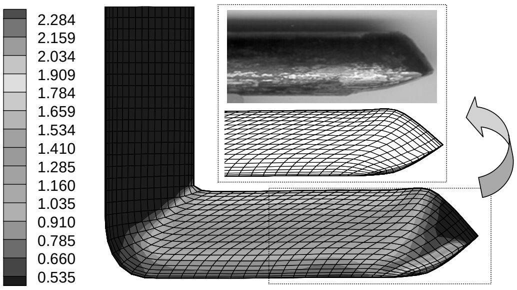


Fig. 9. Comparison of deformed shapes obtained from simulation and experiments with CP-Ti Grade-1 and numerically predicted effective strain distribution

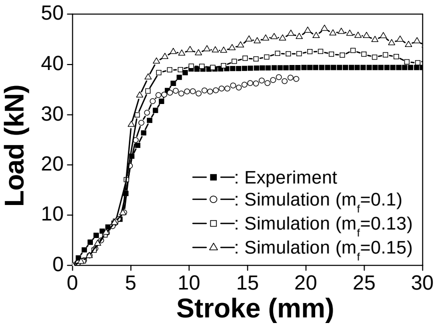


Fig. 10. Comparison of load vs. stroke curves obtained from the experiment and simulations with different friction conditions [24]

Equal channel angular extrusion (ECAE) process is an effective method that induces the severe plastic deformation through the channel with an equal cross-section. Therefore, the multi-pass operation can be easily applied to improve the mechanical property of the material. The numerical simulation to investigate the effect of process parameters of the ECAE process such as die corner angle, route (A and C), shear friction factor, and temperature on deformation in plane strain condition was carried out by Lee, et al. [23] in Fig. 9. Since it is not possible to investigate the effect of route B in the two-dimensional plane strain condition, Son, et al. [24, 25] carried out three-dimensional analysis of CP-Ti Grade-1 with a circular cross-section. The resultant deformed shapes obtained from the simulation and experiment are compared in Fig. 10. It was also found out in this figure that load prediction obtained from the simulation with shear friction factor of 0.13 was in good agreement with that obtained from the experiment using the lubricant of MoS_2. This simulation results clearly demonstrate the effect of frictions on the ECAE process. Zhang, et al. [26] also investigated the plastic deformation of CP-Ti by multi-pass equal channel angular extrusion at medium hot working temperatures and Son, et al. [27] the effect of back pressure on deformation in the same process. Dudra and Im [28] and Kim, et al. [29] investigated the void closure of steel in open die forging and ductile fracture in heading process of aluminum alloy, respectively.

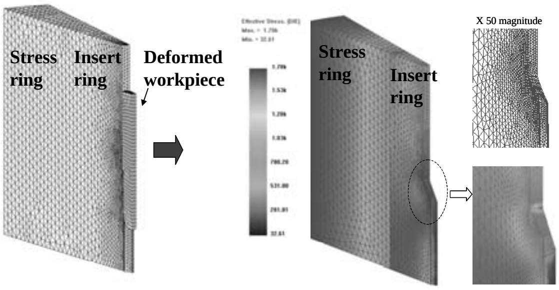


Fig. 11. Elastic deformation and effective stress distribution during the extrusion process of the solid spur gear

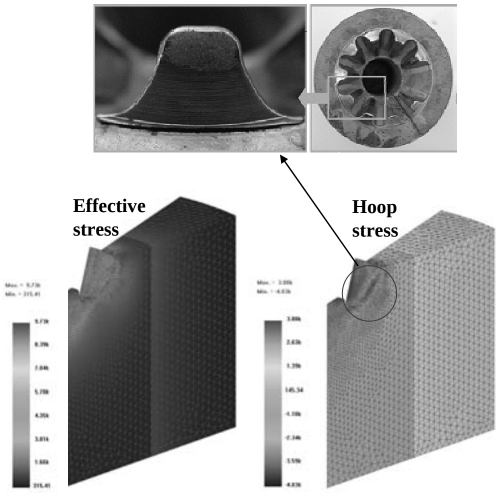


Fig. 12. Distributions of effective and hoop stresses obtained from the elastic analyses of the bevel gear die and photos showing the fracture occurred during forging process of the bevel gear

During the forging process, normal pressure to the dies has the significant influence on the amount of die wear and elastic deformation of the dies and tool life. This is directly linked with thedimensional accuracy of the final forged product as well. Thus, Lee and Im [30] have calculated the amount of die wear and elastic deformation of the axi-symmetric extrusion dies. Song and

Im [31] extended this work by developing the three-dimensional FE elastic program to predict the elastic deformation at the teeth of the spur/bevel gears in extrusion and forging according to the amount of shrink-fit and use of stress ring as followed by the work by Ahn and Im [32]. Fig. 11 shows the deformed shape of the dies magnified by 50 times and effective stress distribution during the extrusion process of the spur gear. This figure shows that the crack can be initiated from the sharp corner subjected to high stress.

Fig. 12 shows the effective stress and hoop stress distributions in closed-die forging and fractured die made of SKD 11. As can be seen in this figure, because effective and hoop stresses were very high in the neighborhood of the root of the teeth, the fracture occurred at the root of the teeth in experiments.

In cold forging process design, the failure caused by surface fatigue is catastrophic. Therefore, the prediction of life cycle of the dies until the initiation of fatigue cracks is of importance for industry. Therefore, local stress approach was employed in order to the life cycles for bevel gear and hexagonal bolt forging. Material used for the die was SKD-11.

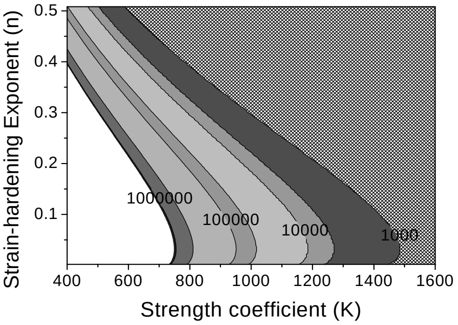


Fig. 13. Rough estimate of the high cycle fatigue life based on material property data

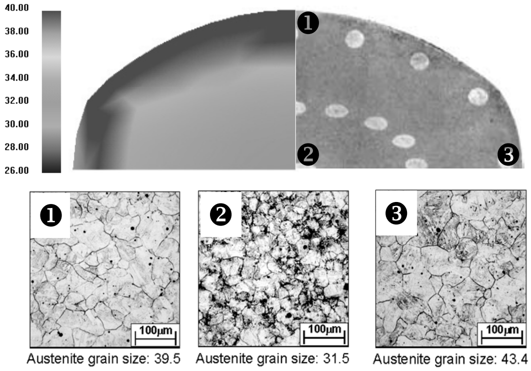


Fig. 14. Comparison of deformed shape and AGS distributions at various points obtained from experiment and FE simulation [35]

In case of the bevel gear forging, although the stress ring was considered, the die was failed just within first few strokes of processing at the laboratory die try out as shown in Fig. 12. Thus, Saroosh, et al. [33] tried to estimate the tool life based on the material property of the workpiece as shown in Fig. 13. In this figure, rough estimate of the tool life can be determined easily by just checking the K and n values of the material.

The mechanical properties are strongly dependent on the microstructure evolution during and after deformation. Thus, they were analyzed in order to efficiently control the mechanical property of the billet and heat treatment condition after deformation. To achieve this, Kwon, et al. [34,35] integrated CAMP*roll* with the AGS evolution model available in the literature. The resultant AGS prediction was in good agreement with the one obtained from the experiment as shown in Fig. 14. Lee, et al. [36] extended this work by deriving the microstructure evolution model for AISI4135 steel for square-diamond pass hot bar rolling based on the torsion test. Kwon and Im [37] used the simulation tool for determining the process sequence design to obtain more homogeneous and refined microstructure during hot bar rolling.

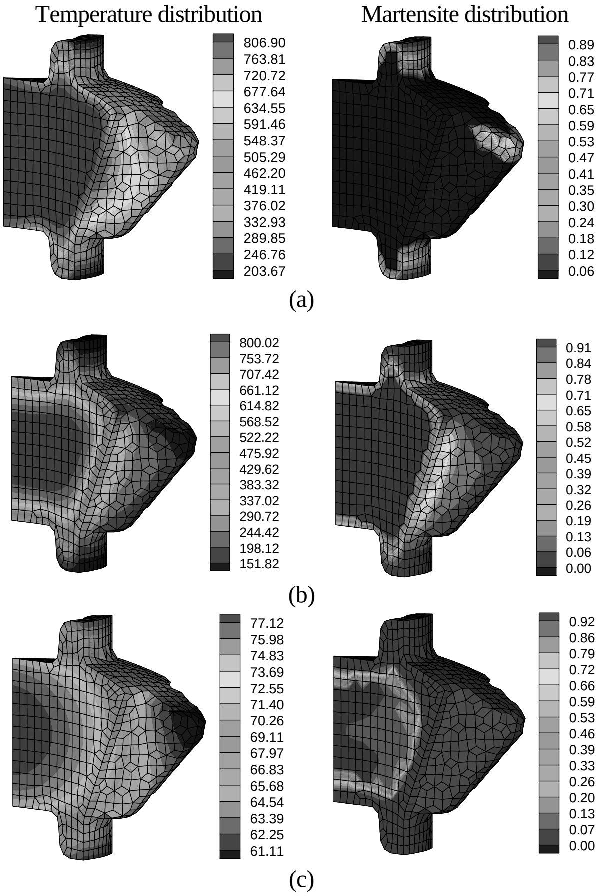


Fig. 15. Distributions of temperature and martensite phase after (a) 3.0, (b) 4.0 and (c) 30.0 sec. of quenching obtained from FE analyses [38]

Mechanical parts made of low carbon steel are commonly used for the power train components and thus required to have high strength, hardness, and wear/fatigue resistance. For this, quenching has been commonly adopted in the manufacturing process of such mechanical parts. In order to predict the distributions of various phases generated during the quenching process, which strongly have an effect on the mechanical properties, Johnson-Mehl-Avrami-Kolmogorov equation for the diffusional transformation and

Koistinen and Marburger's equation to handle the diffusionless transformation were employed in the heat treatment FE analysis by Kang and Im [38,39].

Fig. 15 shows the temperature and the corresponding martensitic phase distributions during the quenching process after deformation stage of the bevel gear forming. According to this figure, the corner and edge areas were rapidly cooled down and thus martensite phase was generated in these areas for the first time. When the time passed, martensite phase expanded to the inside surface of the bevel gear with decrease of the temperature. Although the temperature was very low after 30.0 seconds, however, the martensite phase did not expand any more to the direction of the center-line.

Recently, this work has been extended to couple with the transformation induced plastic deformation during heat treatment by Kang and Im [40] to investigate the effect of temperature variation and phase transformation on the dimensional change and stress distribution as shown in Fig. 16.

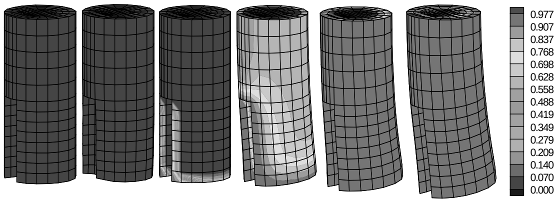


Fig. 16. Variations of deformed shape and distributions of martensite phase of the shaft with keyhole after quenching at various times [40]

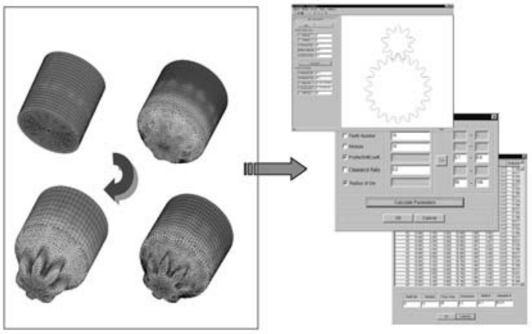


Fig. 17. Computer-aided-design system for the cold forward extrusion of spur gear

6. Computer-aided design system

In the field of metal forming, Chu, et al. [41] has initiated the process sequence design of the axi-symmetric part of nozzle type. Process design systems based on rule or knowledge bases have been actively developed for an axi-symmetric geometry afterwards by Kim and Im [42-44] and Song and Im [45].

However, the development of design system for complex three-dimensional forming processes is still at development stage. In this area, three examples of the computer-aided design systems for the three-dimensional spur gear extrusion process by Song and Im [46,47], flat-die hot extrusion process by Lee, et al. [19] and Lee and Im [20], and roll pass/profile design in bar rolling by Kim and Im [48] and Kwon and Im [49] developed so far at the laboratory level will be introduced.

The computer-aided-design system for the cold extrusion of the spur gear developed under the graphical user interface environment can be seen in Fig. 17. The effect of gear geometry such as total tooth number, profile shift coefficient, and module on deformation mechanics was investigated by the three-dimensional FE program CAMP*form*-3D in terms of complete formation of the gear teeth and the level of forming loads. Based on three-dimensional FE analyses and literature survey, necessary rule bases including a limiting extrusion ratio at the cross-section of the root and a limiting ratio between extrusion ratios of the addendum and root of a gear were established in [31].

The developed design system can provide a feasible set of gear and pinion geometries for a given input data, satisfying required product capacities such as contact ratio and bending strength. Thus, design engineer can easily choose the better product design, depending on individual priority of the product and reduce the lead time and cost required at the initial design stage of spur gear extrusion.

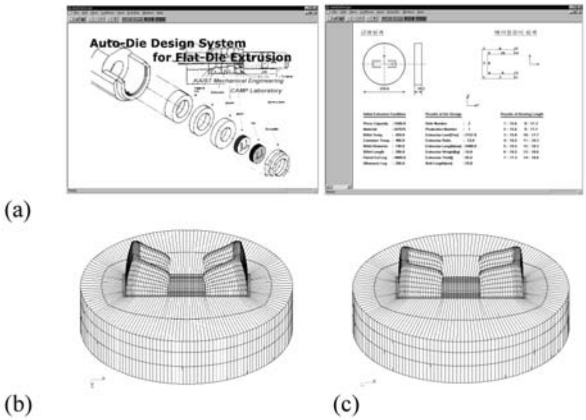


Fig. 18. (a) Developed computer-aided design system for flat-die hot extrusion process and deformed shapes of the workpiece with (b) constant bearing lengths of 5mm and bearing length designed from this system

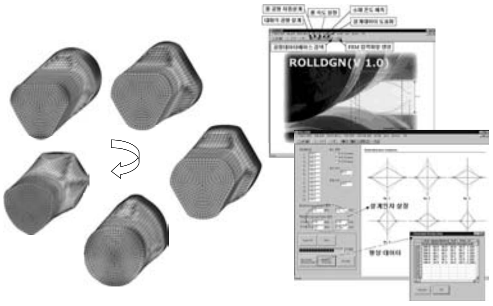


Fig. 19. Roll pass/profile computer-aided-design system

Fig. 18 shows the computer-aided-design system for the flat-die hot extrusion process. In this system, the length distribution of bearing land at the flat-die outlet can be generated using the exit velocity distribution obtained from FE simulations in consideration of cross- sectional thickness and distance from the die center of the die exit section. As can be seen in this figure, the workpiece shape extruded from the flat die with the designed bearing length is better than that extruded from the flat die with a constant bearing length since the designed bearing length gives the rather uniform exit velocity of the workpiece.

Finally, the computer-aided-design system as shown in Fig. 19 has been developed to support the roll pass/profile design for bar rolling, where simple shape like round and square bars are produced. In the process design of bar rolling, material flow must be accurately predicted to minimize defects formation in the product, and then engineering data such as roll separating force and required motor power must be considered at the design stage. Depending on the design methodology, roll pass sequences were properly determined consisting of roughing, breaking-down, and finishing pass sequences. Therefore, in the developed system, numerous formulas for spread prediction and engineering calculation were implemented and such design data was provided to the users in a table form and graphic display. Then, the process design can be modified and redesigned interactively to optimize the process design. A local automatic roll groove design scheme was implemented to easily find roll groove geometries, which will guarantee the area reduction ratio at each pass. Roll speed set-up considering forward slip and an approximate temperature prediction model was also implemented to take into account the necessary rolling conditions for a given facility arrangement. All the design data can be stored as process database and searched for the next design process to minimize the design cost and time.

Jung and Im [50-54] had introduced artificial intelligence technique with the help of finite element simulations for fuzzy shape control in cold rolling and determination of the roll speed variation based on roll separating force and tension variations in hot rolling.

7. Other research works investigated

Other than metal forming areas, there are several processing techniques such as casting and compression molding of composites as well as injection molding. Because of the past working experience at the near net-shape engineering research center at the Ohio State University, finite element simulation programs were developed for solidification studies and shrinkage prediction due to solidification by Tszeng, et al. [55] and Chen, et al. [56-59]. This work has been expanded for semi-solid forging simulation area by Yoon, et al. [60,61].

The compression molding is widely used for fabricating thermoset composites for possible candidate for exterior body panel and home interior applications. Thus, the material flow including curing due to polymerization and fiber orientation distributions were investigated for compression molding of sheet molding compounds by Fan, et al., Lee, et al., Kim, et al., Jeong, et al., Kim, et al., Kwak, et al., Cheon, et al., and Lee, et al. [62-72].

The filling, cooling, post filling, and fiber orientation analyses including fiber orientation distribution studies in injection molding without or with short fibers were carried out by Han and Im [73-76] as well. Choi and Im [77] predicted the shrinkage and warpage due to residual stress in the injection molded part. Kang, et al. [78] had investigated the relation between joint strength and glass-fiber weight fraction of the flat plate made of glass-mat reinforced thermoplastics under tensile loading. Recently, Choi, et al. [79,80] have investigated the analysis of micro-channel flow by introducing a fringe element reconstruction method.

8. Conclusions

Various aspects of research topics involved with forming simulations and its industrial applications are reviewed and recaptured in this paper. Although the various simulation tools are available in the market, it is important to understand and determine its own limitation for industrial usage of the simulation tools. According to the research works carried out so far, it is important to determine the right boundary conditions and material properties for fully utilizing the simulation tools. The size effect should be carefully examined for applications for micro-forming simulations. For three dimensional analyses the mesh generation and computation time management are important issues to be solved yet. Also, further development of design system for three-dimensional industrial applications is necessary.

Acknowledgements

The authors wish to thank late Prof. S. Kobayashi, Prof. T. Altan, Drs. J.H. Jung, J.Y. Jung, S.Y. Kim, Y.W. Hahn, J.H. Yoon, G.A. Lee, D.Y. Kwak, K.H. Han, J.S. Cheon, H.C. Kwon, J.H. Song, D.S. Choi, S.H. Kang, I.H. Son, Prof. Y. Lee, Dr. P.B. Hussein, Prof. Z.D. Zhang, Prof. P.D. Hodgson, Messrs. S.G. Oh, E.D. Chu, K.T. Kim, S.H. Kim, S.M. Lee, S.C. Ahn, W.Y. Choi, W.S. Kang, J.H. Min, J.W. Lee, J.H. Lee, H.Y. Kim, and M.A. Saroosh for working together to develop the programs and sharing valuable supports and suggestions.Acknowledgements should be placed before reference. This work was supported by the Korea Science and Engineering Foundation (KOSEF) through the National Research Lab. Program funded by the Ministry of Science and Technology (No. R0A-2006-000-10240-0).

References

[1] C.H. Lee, S. Kobayashi, New Solutions to Rigid Plastic Deformation Problems using a Matrix Method, Journal of Engineering for Industry-Transactions of the ASME' 95 (1973) 865-873.

[2] P.R. Burte, Y.T. Im, T. Altan, S.L. Semiatin, Measurement and Analysis of Heat Transfer and Friction during Hot Forging, Journal of Engineering for Industry-Transactions of the ASME 112 (1990) 337-344.

[3] Y.T. Im, Investigation of Heat Transfer and Simulation of Metal Flow in Hot Upsetting, Journal of Engineering for Industry-Transactions of the ASME 111 (1989) 332-339.

[4] Y.T. Im, S. Kobayshi, Finite Element Analysis of Plastic Deformation of Porous Materials, Metal Forming and

Impact Mechanics (Edited by S.R. Reid), Pergamon Press, Oxford (1985) 103-122.

[5] Y.T. Im, S. Kobayashi, Coupled Thermo-viscoplastic Finite Element Analysis of Plane-Strain Compression of Porous Materials, Advanced Manufacturing Processes 1 (1986) 269-291.

[6] Y.T. Im, S. Kobayashi, Analysis of Axisymmetric Forging of Porous Materials by the Finite Element Method, Advanced Manufacturing Processes 1 (1986) 473-499.

[7] S.G. Oh, Y.T. Im, An experimental Study on Densification of Sintered Iron P/M Cylindrical Billets in Forward Extrusion, Journal of Materials Processing Technology 37 (1993) 499-511.

[8] Y.T. Im, J.S. Cheon, S.H. Kang, Determination of Friction Condition by Geometrical Measurement of Backward Extruded Aluminum Alloy Specimen, Trans. ASME, Journal of Manufacturing Science and Engineering 124 (2002) 409-415.

[9] Y.T. Im, S.H. Kang, J.S. Cheon, Finite Element Investigation of Friction Condition in a Backward Extrusion of Aluminum Alloy, Trans. ASME, Journal of Manufacturing Science and Engineering 125 (2003) 378-383.

[10] Y.T. Im, S.H. Kang, J.S. Cheon, A Novel Technique of Friction and Material Property Measurement by Tip Test in Cold Forging, Proceedings of the Institution of Mechanical Engineers part B Journal of Engineering Manufacture 220 (2006) 81-90.

[11] S.H. Kang, J.H. Lee, J.S. Cheon, Y.T. Im, The Effect of Strain-Hardening on Frictional Behavior in Tip Test, International Journal of Mechanical Sciences 46 (2004)855-869.

[12] S.Y. Kim, Y.T. Im, Three-Dimensional Finite Element Simulation of Shape Rolling of Bars, International Journal of Forming Processes 3 (2000) 253-278.

[13] S.Y. Kim, Y.T. Im, Steady State Finite Element Simulation of Bar Rolling Processes Based on Rigid-Visoplastic Approach, International Journal for Numerical Methods in Engineering 63 (2005) 1583-1603.

[14] D.Y. Kwak, J.S. Cheon, Y.T. Im, Remeshing for Metal Forming Simulations - Part I: Two-Dimensional Quadrilateral Remeshing, International Journal for Numerical Methods in Engineering 53 (2002) 2463-2500.

[15] D.Y. Kwak, Y.T. Im, Remeshing for Metal Forming Simulations - Part II: Three-Dimensional Hexahedral Mesh Generation, International Journal for Numerical Methods in Engineering 53 (2002) 2501-2528.

[16] W.Y. Choi, D.Y. Kwak, I.H. Son, Y.T. Im, Tetrahedral Mesh Generation based on Advancing Front Technique and Optimization Scheme, International Journal for Numerical Methods in Engineering 58 (2003) 1857-1872.

[17] W.Y. Choi, I.H. Son, Y.T. Im, Locally Refined Tetrahedral Mesh Generation based on Advancing Front Technique with Optimization and Smoothing Scheme, Communications in Numerical Methods in Engineering 20 (2004) 681-688.

[18] I.H. Son Y.T. Im, Localized Remeshing Techniques for Three Dimensional Metal Forming Simulations with Linear Tetrahedral Elements, International Journal for Numerical Methods in Engineering 67 (2006) 672-696.

[19] G.A. Lee, D.Y. Kwak, S.Y. Kim, Y.T. Im, Analysis and Design of Flat Die Extrusion Process 1. Three-Dimensional Finite Element Analysis, International Journal of Mechanical Sciences 44 (2002) 915-934.

[20] G.A. Lee, Y.T. Im, Analysis and Die Design of Flat Die Extrusion Process 2. Numerical Design of Bearing Lengths, International Journal of Mechanical Sciences 44 (2002) 935-946.

[21] S.Y. Kim, Y.T. Im, Parallel Processing of 3D Rigid-Viscoplastic Finite Element Analysis using Domain Decomposition and Modified Block Jacobi Preconditioning Technique, Journal of Materials Processing Technology 134 (2003) 254-264.

[22] J.S. Cheon, S.Y. Kim, Y.T. Im, Three-Dimensional Bulk Metal Forming Simulations under a PC Cluster Environment, Journal of Materials Processing Technology 140 (2003) 36-42.

[23] J.H. Lee, I.H. Son, Y.T. Im, Finite Element Investigation of Equal Channel Angular Extrusion Process, Material Transactions, The Japan Institute of Metals 47 (2004) 2165-2171.

[24] I.H. Son, Y.G. Jin, Y.T. Im, Finite Element investigations of friction condition in equal channel angular extrusion, Journal of Achievements in Materials and Manufacturing Engineering 17 (2006) 285-288.

[25] I.H. Son, Y.G. Jin, Y.T. Im, S.H. Chon, J.K. Park, Sensitivity of Friction Condition in Finite Element Investigations of Equal Channel Angular Extrusion," Material Science and Engineering A 445-446 (2007) 676-685.

[26] Z.J. Zhang, I.H. Son, Y.T. Im, J.K. Park, Finite Element Analysis of Plastic Decformation of CP-Ti by Multi-Pass Equal Channel Angular Extrusion at Medium Hot-Working Temperature," Material Science and Engineering A 447 (2007) 134-141.

[27] I.H. Son, J.H. Lee, Y.T. Im, Finite Element Investigation of Equal Channel Angular Extrusion with Back Pressure, Journal of Materials Processing Technology 171 (2006) 480-487.

[28] S. Dudra, Y.T. Im, Analysis of Void Closure in Open-Die Forging," International Journal of Machine Tools and Manufacture 30 (1990) 65-75.

[29] H.S. Kim, Y.T. Im, M. Geiger, Prediction of Ductile Fracture in Cold Forging of Aluminum Alloy, Journal of Engineering for Industry-Transactions of the ASME 121 336-344.

[30] G.A. Lee, Y.T. Im, Finite-Element investigation of the Wear and Elstic Deformation of Dies in Metal Forming, Journal of Materials Processing Technology 89-90 (1999) 123-127.

[31] J.H. Song, Y.T. Im, Determination of a Major Design Parameter for Forward Extrusion of Spur Gears, ASME Trans., Journal of Manufacturing Science and Engineering 126 (2004) 255-263.

[32] S.C. Ahn, Y.T. Im, Optimal Design of Dimension of Extrusion Die with Multi Stress Rings, KSME Trans. A 26 (2002) 2211-2218.

[33] M.A. Saroosh, H.C. Lee, Y.T. Im, S.W. Choi, D.L. Lee, High-Cycle Fatigue Life Prediction of Cold Forging Tools based on Workpiece Material Property, will appear in Journal of Materials Processing Technology (2007).

[34] H.C. Kwon, Y.S. Lee, S.Y. Kim, J.S. Woo, Y.T. Im, Numerical Prediction of Austenite Grain Size in Round-Oval-Round Bar Rolling, The Iron and Steel Institute of Japan 43 (2003) 676-683.

[35] H.C. Kwon, Y.S. Lee, Y.T. Im, Experimental and Numerical Prediction of Austenite Grain Size Distribution in Round-

oval Shape Rolling, The Iron and Steel Institute of Japan 43 (2003) 1967-1975.

[36] H.W. Lee, H.C. Kwon, Y.T. Im, P.D. Hodgson Zahiri, Local Austenite Grain Size Distribution in Hot Bar Rolling of AISI4135 Steel, The Iron and Steel Institute of Japan 45 (2005) 706-712.

[37] H.C. Kwon Y.T. Im, Process Design for Refinement and Homogenization of Microstructure in Bar Rolling, Journal of Materials Processing Technology 167 (2005) 273-282.

[38] S.H. Kang, Y.T. Im, Three-Dimensional Finite Element Analysis of Quenching Process of Plain Carbon Steel with Phase Transformation, Metallurgical and Materials Transactions A 36 (2005) 2315-2325.

[39] S.H. Kang, Y.T. Im, Finite Element Investigation of Multi-Phase Transformation within Carburized Carbon Steel, Journal of Materials Processing Technology 183 (2007) 241-248.

[40] S.H. Kang, Y.T. Im, Three-Dimensional Thermo-Elastic-Plastic Finite Element Modeling of Quenching Process of Plain-Carbon Steel in Couple with Phase Transformation, International Journal of Mechanical Sciences, 49/4 (2007) 423-439.

[41] E.D. Chu, Y.T. Im, N.S. Kim, J.S. Lee, Process Sequence Design of Large Axi-Symmetric Forging Product of AISI4130 in Nozzle Type, Journal of Materials Processing Technology 48 (1995) 143-149.

[42] H.S. Kim, Y.T. Im, Expert System for Multi-Stage Cold-Forging Process Design with a Re-Designing Algorithm, Journal of Materials Processing Technology 54 (1995) 271-285.

[43] H.S. Kim, Y.T. Im, Multi-Stage Cold Forging Process Design with A* Searching Algorithm, Transactions, North American Manufacturing Research Institution of the Society of Manufacturing Engineers NAMRI/SME 24 (1996) 161-166.

[44] H.S. Kim, Y.T. Im, An Expert System for Cold Forging Process Design based on a Depth-First Search, Journal of Materials Processing Technology 95 (1999) 262-274.

[45] J.H. Song, Y.T. Im, Expert System for Process Sequence Design of a Ball Stud, Journal of Materials Processing Technology 89 (1999) 72-78.

[46] J.H. Song, Y.T. Im, Development of a Computer-Aided-Design System of Cold Forward Extrusion of a Spur Gear, Journal of Materials Processing Technology 153-154 (2004) 821-828.

[47] J.H. Song, Y.T. Im, The Applicability of Process Design System for Forward Extrusion of Spur Gears, Journal of Materials Processing Technology 184 (2007) 411-419.

[48] S.H. Kim, Y.T. Im, A Knowledge-based Expert System for Roll Pass and Profile Design for Shape Rolling of Round and Square Bars, Journal of Materials Processing Technology 89 (1999) 145-151.

[49] H.C. Kwon, Y.T. Im, Interactive Computer-Aided-Design System for Roll Pass and Profile Design in Bar Rolling, Journal of Materials Processing Technology 123 (2002) 399-405.

[50] J.Y. Jung, Y.T. Im, L.K. Hyung, Development of Fuzzy Control Algorithm for Shape Control in Cold Rolling, Journal of Materials Processing Technology 48 (1995) 187-195.

[51] J.Y. Jung, Y.T. Im, Fuzzy-Control Simulation of Cross-Sectional Shape in Six-High Cold Rolling Mills, Journal of Materials Processing Technology 62 (1996) 61-69.

[52] J.Y. Jung, Y.T. Im, Simulation of Fuzzy Shape Control for Cold-Rolled Strip with Randomly Irregular Strip Shape, Journal of Materials Processing Technology 63 (1997) 248-253.

[53] J.Y. Jung, Y.T. Im Fuzzy Algorithm for Calculating Roll Speed Variation based on Roll Separating Force in Hot Rolling, International Journal of Mechanical Sciences 42 (2000) 249-272.

[54] J.Y. Jung, Y.T. Im, Fuzzy Control Algorithm for the Prediction of Tension Variations in Hot Rolling, Journal of Materials Processing Technology 96 (1999) 163-172.

[55] T.C. Tszeng, Y.T. Im, S. Kobayashi, Thermal Analysis of Solidification by the Temperature Recovery Method, International Journal of Machine Tools and Manufacture 29 (1989) 107-120.

[56] Y.H. Chen, Y.T. Im, Analysis of Solidification in Sand and Permanent Mold Castings and Shrinkage Prediction, International Journal of Machine Tools and Manufacture30 (1990) 175-189.

[57] Y.H. Chen, Y.T. Im, Z.H. Lee, Three Dimensional Finite Element Analysis with Phase Change by Temperature Recovery Method, International Journal of Machine Tools and Manufacture 31 (1991) 1-7.

[58] Y.H. Chen, Y.T. Im, J.S. Yoo, Finite Element analysis of Solidification of Aluminum with Natural Convection, Journal of Materials Processing Technology 52 (1995) 592-609.

[59] Y.H. Chen, Y.T. Im, J.K. Lee, Finite Element Simulation of Solidification with Momentum, Heat and Species Transport, Journal of Materials Processing Technology 48 (1995) 571-579.

[60] J.H. Yoon, Y.T. Im, N.S. Kim, Rigid-Thermoviscoplastic Finite-Element Analysis of the Semi-Solid Forging of Al2024, Journal of Materials Processing Technology 89-90 (1999) 104-110.

[61] J.H. Yoon, Y.T. Im, N.S. Kim, Finite Element Modeling of the Deformation Behavior of Semi-Solid Materials, Journal of Materials Processing Technology 113 (2001) 153-159.

[62] J.D. Fan, L.J. Lee, J. Kim, Y.T. Im, Cure Analysis of Sheet Molding Compound in Molds with Substructures, Polymer Engineering and Science 29 (1989) 740-748.

[63] L.J. Lee, J.D. Fan, J. Kim, Y.T. Im, Flow Analysis of Sheet Molding Compounds in Compression Molding, International Polymer Processing 6 (1991) 61-72.

[64] J. Kim, Y.C. Shiau, L.J. Lee, Y.T. Im, Compression Molding Simulation of Chopped Fiber Reinforced Polymeric Composites in Plate-Rib Type Geometry, Polymer Composites 13 (1992) 97-107.

[65] K.T. Kim, Y.T. Im, Experimental Study on Physical Properties of Compression Molded SMC Parts under Plane Strain Condition, Composite Structures 35 (1996) 131-141.

[66] J.H. Jeong, K.T. Kim, Y.T. Im, Plane-Strain Compression Molding Analysis of Sheet Molding Compounds in Flat and Cross-Sectional T-Shape Molds, Journal of Materials Processing Technology 57 (1996) 320-331.

[67] J.H. Jeong, Y.T. Im, Estimation of Sink Mark Depth in Compression Molded SMC Parts with Substructures, Journal of Composite Materials 31 (1997) 2161-2187.

[68] S.Y. Kim, Y.T. Im, Three-Dimensional Thermo-viscoplastic Analysis of Compression Molding of Sheet Molding Compounds with Fiber Volume Fraction Prediction, Journal of Materials Processing Technology 63 (1997) 631-636.

[69] D.Y. Kwak, J.H. Jeong, J.S. Cheon, Y.T. Im, Optimal Design of Composite Hood with Reinforcing Ribs through Stiffness Analysis, Composite Structures 38 (1997) 351-359.

[70] J.S. Cheon, Y.T. Im, Determination of Short Glass-Fiber Volume Fractions in Compression Molded Thermoset Composites-Experimental, Journal of Composite Materials 33 (1999) 525-546.

[71] J.S. Cheon, Y.T. Im, Determination of Short Glass-Fiber Volume Fractions in Compression Molded Thermoset Composites-Numerical, Journal of Composite Materials 33 (1999) 547-566.

[72] S.M. Lee, J.S. Cheon, Y.T. Im, Experimental and Numerical Study of the Impact Behavior of SMC Plates, Composite Structures 47 (1999) 551-561.

[73] K.H. Han, Y.T. Im, Compressible Flow Analysis of Filling and Post-Filling in Injection Molding with Phase-Change Effect, Composite Structures 38 (1997) 179-190.

[74] K.H. Han, Y.T. Im, Effect of Closure Approximation on Fiber Orientation Distribution in Injection Molding, International Journal of Forming Processes 3 (2000) 213-234.

[75] K.H. Han, Y.T. Im, Modified Hybrid Closure Approximation for Prediction of Flow-Induced Fiber Orientation, Journal of Rheology 43 (2000) 569-589.

[76] K.H. Han, Y.T. Im, Numerical simulation of Three-Dimensional Fiber Orientation in Injection Molding including Fountain Flow Effect, Polymer Composites 23 (2002) 222-238.

[77] D.S. Choi, Y.T. Im, Prediction of Shrinkage and Warpage in Consideration of Residual Stress in Integrated Simulation of Injection Molding, Composite Structures 47 (1999) 655-665.

[78] W.S. Kang, J.H. Min, J.W. Lee, Y.T. Im, Estimation of Bolted Joint Strength of Flat Plate of Glass-Mat Reinforced Thermoplastics, KSME Trans. A 27 (2003) 1636-1643.

[79] D.S. Choi, S.S. Lee, Y.T. Im, Fringe Element Reconstruction for Front Tacking for Three-Dimensional Incompressible Flow Analysis, International Journal for Numerical Methods in Fluids 48 (2005) 631-648.

[80] D.S. Choi, S.W. Lee, S.S. Lee, Y.T. Im, Micro-Channel Flow Analysis by a Fringe Element Reconstruction Method," Journal of Micromechanics and Microengineering 16 (2006) 571-579.