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論文名	「Study on Analyses of Plastic Deformation of Al- and Mg- Alloys by Using Finite Controlled Volume Method Simulation」 （有限差分法シミュレーションによるアルミニウムおよびマグネシウム合金の塑性変形解析に関する研究）
論文審査委員	主査　東　健司 副査　今野　豊彦 副査　高杉　隆幸

Summary

Most of the industry (specially the steels, automobiles, aircrafts, railways) deals the structural materials not only as tools but also as its bodies or frames. Recently, the materials designers are subjected to relieve energy consumption as possible for the energy efficiency and environmental friendliness. Light metals such as Al or Mg are expected as next generation structural materials with its lightness and high specific strength. The low density with sufficient stiffening can decrease the energy to move the structure. Up to date, plenty of works have been carried out to understand the plastic deformation on these metals.

Plastic deformation depends on its deformation mechanisms in metal flow which have been reported as followed; diffusional creep, grain boundary sliding, slip at high or elevated temperatures, and slip, twin at low temperatures. Each deformation mechanism has its constitutive equation which explains the metal's plastic deformation in the relationship among the stress, strain rate, temperature and grain size. These constitutive equations can be applied to predict any material's flow behavior at high temperatures or superplastic behavior with limited number of some essential experiments.

The finite element method simulation, which was modeled with constitutive equation, has been used to understand the plastic deformation of metals. By accompanying appropriate simulation analysis to experiments, one can achieve the understandings on the plastic deformation behavior of interesting materials faster, easily and cost-effectively because of extensively simplified experimental steps.

However, this computer-aided analysis has shown lack of applicability because of exponentially increasing calculation performance to perform large plastic deformation. Therefore, a study to analyze high-strain plastic deformation with more enhanced method than finite element method is required.

In this work, the author chose the finite controlled volume method code (MSC.SuperForge™) for simulation analyses in order to understand the plastic deformation behavior of light metals like Al or Mg alloys, and successfully performed various high-strain metalworking simulations. For example, the equal channel angular extrusion, the double shear extrusion and the superplastic forging, which have been recently issued in academic or industrial needs, were analyzed in this work. With direct or indirect, confirming experiments for the simulation, more realistic modelings were attempted and analyzed.

This thesis includes 7 chapters.

In chapter 1, the backgrounds of choosing light metals (Al, Mg alloys) were presented as the next generation for strategic structural material. And the relationship between the plastic deformation and deformation mechanism was represented with the constitutive equations and the deformation mechanism map. Brief introduction to finite element method and finite controlled volume method simulations were presented. These will be the bases of modeling of plastic deformation.

In chapter 2, the full 3-dimensional finite controlled volume method simulation successfully analyzed the high-strain plastic deformation of equal channel angular extrusion, while the conventional finite element method simulation for the 3-dimensional high-strain plastic deformation has been recognized as very difficult work. The instantaneous strain, stress, strain rate and temperature distributions during the equal channel angular extrusion processing were visualized. The inhomogeneous strain distributions (0.4 ~ 0.8) at the cross-sectional plane to extrusion direction after 1 pass were detected. The ram speed affects on the stress or temperature distributions; faster ram speed (20 mm/s) caused low heat dissipation during deformation, so the material's flow stress decreased slightly with increased temperature, on the contrary, slow ram speed (1 mm/s) caused sufficient heat dissipation and subsequently increased flow stress with decreasing temperature.

In chapter 3, another high-strain plastic deformation (the double shear extrusion) was analyzed with the finite controlled volume method simulation by using conventional constitutive modeling. 2-dimensional axi-symmetric finite controlled volume method simulations were carried out in order to visualize the proper die geometries at various parametric conditions for the double shear extrusion. The instantaneous strain distributions along the thickness of the pipe and high effective strains (about 2 ~ 4) were detected from the parametric simulations. A round outer taper resulted in a more homogeneous distribution than with a linear outer taper. Applying smaller taper rather than raising temperature could decrease the inhomogeneity of the strain distribution. Moreover, dead zone's possibility was expected in the die with no taper from the distributions of metal flow vector and strain rate at the area where deformed firstly. When there was no outer taper, metal flow was retarded at the corner, which increased the possibility of a dead-zone forming. This indicates the need for a small taper to allow smooth metal flow during double shear extrusion. Optimum die geometry could be predicted for the double shear extrusion from the results of the instantaneous strain distribution. When we changed width of the space, the best die geometry was that has narrow space after upsetting, then wide space between inner and outer walls, smaller outer taper and large inner taper. Because the strain distribution was higher and homogeneous, and there were no gaps in the inner wall of the pipe and die.

In chapter 4, an analysis linking the results by experiments and those by simulation was conducted. Full 3-dimensional finite controlled volume method simulation for equal channel angular extrusion process was carried out. It represented the non-uniform deformation by detecting regional gradients from the inner arc to the outer arc area. A prolonged strain contour may come from backward dragging force caused by friction on the material/die interface. Particle tracking analyses showed similar to the contoured results but presented more detailed histories of effective strain and stress for any local position. Load-stroke and grid distortions could be visualized from 3-dimensional symmetric simulation, which showed slight flow-localization. The Vickers hardness results supported the non -uniform deformation during 1 pass of equal channel angular extrusion correlating with simulation results of effective strain and effective stress distribution. The local instantaneous strain distribution along the line from top and bottom of the rod obtained by finite controlled volume method simulation was in line with the hardness results for the actual equal channel angular extrusion in Al-Mg alloy. Moreover, higher hardness values in the backward region could be explained by hydrostatic stress state before the deforming zone. In this work, the reliability between simulation and experiment has been confirmed.

In chapter 5, another analysis linking experiment and simulation was carried out for superplastic forging. The changes in mechanical properties such as effective strain or stress distributions were discovered by 3-dimensional finite controlled volume simulation of virtual forging for Zn-22Al (wt%) eutectoid alloys. Forging simulations on Zn-22Al eutectoid alloys, which have different microstructures transformed by different thermo-mechanical controlling processes, were carried out. Two models, which were based on constitutive equations of creep or grain boundary sliding, resulted local instability in the high strain rate region (the corner) in the finite controlled volume method simulation on the seismic damper of Zn-22Al alloy. Higher and concentrated strain distribution, lower level of stress distribution, and higher strain rate were detected at the corner. The followed cold forging of seismic dampers confirmed the prediction of simulation. The actual forging experiments confirmed that microstructure played a great role in superplastic forging. The corner where most severe deformation is expected showed low temperature superplasticity in the extruded Zn-22Al, on the contrary, the corner in the rolled one showed not sufficient formability. A proper thermo-mechanical controlling processed one with fine grain size and non-lamella structure showed low-leveled and uniform deformation in effective stress. However, another sample, which had relatively large grain size and ~ 15 vol% lamella structure, required more higher load to be deformed.

In chapter 6, a modeling considering dynamic recrystallization was attempted in finite controlled volume method simulation. The actual double shear extrusion experiment was carried out at 573 K, and serial microstructures were measured at the interesting regions where were predicted to be severely deformed. The double shear extrusion processed product had uniform and refined grain size. In the microscopic measurements, dynamic recrystallization in some range of strain (up to ~ 0.7) has occurred during double shear extrusion. During dynamic recrystallization, there existed not only coarse- but also fine- grains, and combined grain size for mixed grains (coarse-grain group and fine-grain group) was represented. By finite controlled volume method simulation based on typical constitutive model, the strain distribution was detected during double shear extrusion. The combination of the grain size distributions by actual double shear extrusion experiment and the instantaneous strain distribution by simulation enabled to determine the relationship of dynamically recrystallized grain size and instantaneous strain distribution. Then, new model with flow stress, which was calculated by the constitutive equations determined by the parameters such as temperature, strain, strain rate, dynamically recrystallized grain size, has been constructed. Comparison of instantaneous distributions of effective strain, stress and strain rate for two models revealed that the model considering dynamic recrystallization predicted more clearly the local stress concentration on high strain rate regions.

In chapter 7, the concluding remarks summarized this thesis. In short, High-strain plastic deformations such as equal channel angular extrusion, double shear extrusion could be analyzed successfully by finite controlled volume method simulation. The hardness results in equal channel angular extrusion of Al-Mg alloy indicated the local inhomogeneous strain distribution as predicted in simulation. This experimental result indicated that the results from simulation were reliable to real experiment. Forging simulation in Zn-22Al alloy, which showed that superplastic deformation had good formability, supported above statement. The instantaneous strain distribution achieved by finite controlled volume method simulation predicted the optimum die geometry in double shear extrusion. By combining strain (by simulation) and d (by experiment), new constitutive model was constructed with considering dynamic recrystallization. This work will be helpful to who may want to predict the metalworking with least actual test, or may want to confirm his metalworking results with simulation.

List of Publications

No.	Title of the Article	Author(s)	Journal's Name, Vol., Pages (Year)	Corresponding Chapter
1	The effect of ram speed on mechanical and thermal properties in ECAE process simulation	S.W. Chung W.J. Kim M. Kohzu K. Higashi	Mater. Trans., Vol. 44, No.5, pp. 973-980 (2003)	Chapter 2
2	The effect of friction coefficient on mechanical properties during full 3-D ECAE simulation	S.W. Chung W.J. Kim K. Higashi	Proc. of 5th Int. Conf. on Oxford Kobe Materials Seminar for Automotive materials, p.252 (Kobe, Japan, 2002)	Chapter 2
3	The effect of die geometry on the double shear extrusion by parametric FVM simulation	S.W. Chung W.J. Kim K. Higashi	Scripta Mater., Vol. 51, No. 11, pp.1117-1122 (2004)	Chapter 3
4	The non-uniform behavior during ECAE process by 3-D FVM simulation	S.W. Chung H. Somekawa T. Kinoshita W.J. Kim K. Higashi	Scripta Mater., Vol. 50, No. 7, pp. 1079-1083 (2004)	Chapter 4
5	Optimizing Forming-Process for Seismic Damper Device using Superplastic Zn-Al alloy	S.W. Chung T. Tanaka L.F. Chaing K. Makii A. Kushibe M. Kohzu K. Higashi	Proc. of 3rd European Conference on Superplastic Forming, Euro-SPF04, pp. 81-86 (Albi, France, 2004)	Chapter 5

6	A finite volume controlled method simulation on the double shear extrusion of Mg-3Al-1Zn alloy with model considering dynamic recrystallization	S.W. Chung H. Watanabe T. Mukai H. Somekawa W.J. Kim K. Higashi	Submitted in Acta Materilia (2004)	Chapter 6
7	Superplastic gas pressure forming of fine-grained AZ61 magnesium alloy sheet	S.W. Chung K. Higashi W.J. Kim	Mater. Sci. Eng. A, Vol. 372, No.1-2, pp. 15-20 (2004)	Chapter 6
8	Creep deformation mechanisms in coarse-grained solid solution Mg alloys	S.W. Chung H. Watanabe W.J. Kim K. Higashi	Mater. Trans., Vol. 45, No. 4, pp.1266-1271 (2004)	Chapter 6
9	Superplastic deformation behavior in the commercial AZ61 Mg alloy during biaxial gas-pressure forming	S.W. Chung W.J. Kim K. Higashi	Mater. Sci. Forum., Vol. 419-422, pp. 539-543 (2003)	Chapter 6
10	Superplastic formability of fine-grained AZ61 and AZ31 magnesium alloy sheets and deformation mechanism maps for magnesium alloys	S.W. Chung W.J. Kim	Proc. of 2nd Int. Conf. on Light Materials for Transportation Systems , LiMAT 2001, pp.417-422 (Pusan, Korea, 2001)	Chapter 6

List of Publications Related to This Thesis

No.	Title of the Article	Author(s)	Journal's Name, Vol., Pages (Year)
1	Post-mechanical Properties of Superplastically-forged Zn-22wt%Al Alloy	T. Tanaka S.W. Chung L.F. Chaing K. Makii A. Kushibe M. Kohzu K. Higashi	Key Eng. Mater., Vol. 274-276, pp.283-288 (2004)
2	Post-characteristics of Formed Zn-22 mass%Al Alloy to Seismic Damper for General Residence	T. Tanaka S.W. Chung L.F. Chaing K. Makii A. Kushibe M. Kohzu K. Higashi	Mater. Trans., Vol. 45, No. 4, pp.2542-2546 (2004)
3	Superplasticity in thin magnesium alloy sheets and deformation mechanism maps for magnesium alloys at elevated temperatures	W.J. Kim S.W. Chung C.S. Chung D. Kum	Acta. Mater., Vol. 49, No. 16, pp. 3337-3345 (2001)
4	Superplasticity in a relatively coarse-grained AZ61 magnesium alloy	W.J. Kim S.W. Chung C.W. An K. Higashi	J. Mater. Sci. Lett., Vol. 20, No. 17, pp. 1635-1637 (2001)
5	Superplasticity in fine-grained AZ61 magnesium alloy	W.J. Kim S.W. Chung	Met. Mater. KIM., Vol. 6, No. 3, pp. 255-259 (2000)

審査結果の要旨

有限要素法などのシミュレーションは金属の塑性変形挙動を理解するために用いられてきた手法である。最近 Equal Channel Angular Extrusion (ECAE)法、Double Shear Extrusion (DSE)、室温超塑性鍛造といった新規加工技術が提案され、超微細組織を有する材料の大変形域（強ひずみ）までの変形挙動が注目されている。本論文では、軽金属材料の大変形域までの変形挙動を理解するため、有限体積法を用いた塑性加工シミュレーションを行うシステムを構築した。ここでは、実験による材料パラメータを用いた構成式を確立するともに、このモデルにより解析を行い、さらに解析結果と実験結果の比較から、解析結果の信頼性を確保した現実的なモデルの構築を目指している。

本論文では、以下に述べるような具体的研究成果を得ている。

① ３次元有限差分法シミュレーションを用いて ECAE 加工における高ひずみ塑性変形の解析を行った。その結果、押出方向に沿った断面において不均一なひずみ分布の存在が確認された。また ECAE 加工におけるプレス速度が応力あるいはひずみの分布に影響を及ぼすことを確認した。

② 実験結果と比較した結果、シミュレーションによって解析された ECAE 加工された変形途中のひずみ分布は実際に ECAE 加工された Al-Mg 合金における硬さ試験結果と良い一致を示すことが分かった。

③ 異なる微細組織を有する合金の超塑性鍛造プロセスに関する有限差分法によるシミュレーションを行った。解析結果より、各合金とも高いひずみ速度で変形するコーナー部で局部的に不均一変形することが明らかにされた。

④ 実際の鍛造実験の結果、微細組織が超塑性成形においては重要な役割を果たすことが確認された。微細結晶粒有する Zn-22Al 合金押出材が低温超塑性を発現することを明らかにした。

⑤ 高ひずみ塑性変形において２次元軸対称有限差分法を行いた不均一ひずみ分布の解析結果より最適な金型形状を予測できることを明らかにした。また実験を行うことにより導出した動的再結晶を考慮したモデルは、従来のモデルと比べ、高ひずみ領域における局部的な応力集中をより正確に予測できることを明らかにした。

以上の研究成果は有限差分法シミュレーションを用いたアルミニウムおよびマグネシウム合金の塑性変形に関する解析の有用性を示すものである。この成果は学術的のみならず工業的にも大いに期待できる有益な手法であり、材料技術の一層の高度化に貢献するところ大である。また申請者が自立して研究を行うに十分な能力と学識を

有することを証したものである。

３．最終試験結果の要旨

審査委員会は、平成 16 年 12 月 24 日、委員全員出席のもとに申請者に論文内容の説明を行わせ、関連する諸問題について試問を行った結果、合格と判定した。

４．公聴会の日時

平成 16 年 12 月 24 日、午前 11 時 00 分～12 時 30 分

５．審査委員会の所見

本委員会は、本論文の審査ならびに最終試験の結果から、博士（工学）の学位を授与することを適当と認める。