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Abstract of Thesis

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Title	Deformation Behavior of Metallic Foams in Bulk Forming Processes (バルク加工における発泡金属の変形挙動)

Abstract of Thesis

Metallic foams are attractive materials for weight reduction, high energy absorption and thermal shielding. Even though these advantages, industrial applications are still limited mainly because of low specific strength and difficulties in forming and joining. By bulk forming, metallic foams may lose the advantages due to pore closure and densification. Nevertheless, bulk forming of metallic foams has several advantages in fabrication of components with desired shapes, work hardening, unusual microstructure and controlling pore morphology. Therefore, it is demanded to reveal deformation behavior and to establish forming technology of metallic foams for industrial applications.

In this study, in order to investigate deformation behavior of metallic foams and density change in bulk forming, cold extrusion of sheathed closed cell foams was conducted. Changes in extrusion load and density of foam core were investigated. The extruded billets were severely deformed by high-ratio differential speed rolling to observe the microstructure. To explain compression behavior of metallic foams with porosity change, repeated compression tests of both open and closed cell foams were conducted. Constitutive equations for metallic foams were discussed for numerical simulations.

In chapter 1, background, motivations, purpose and outline of this thesis are described.

In chapter 2, cold extrusion of sheathed closed-cell type aluminum foam was conducted with three extrusion ratios. The load-stroke curve of the sheathed foam was much different from that of solid material. The sheathed foam was densified until the extrusion start with gradually increasing load, then the extruded through the die with high load. In extrusion ratio of 12.96, the density of foam core increased from 0.279 Mg/m^3 to 1.58 Mg/m^3 before the extrusion start, then increased from 1.58 Mg/m^3 to 2.32 Mg/m^3 by passing the die. The density of foam core increased with increasing extrusion ratio. The density before the extrusion start is sensitive to the extrusion ratio.

In chapter 3, closed-cell aluminum foam was deformed by extrusion or by combination process of extrusion and high-ratio differential speed rolling. Cell crushing during the processes induced severe plastic deformation at cell walls, and pore closure leading to effective grain refinement. The achieved grain size was 1.3 μm and the fraction of high angle grain boundaries was 0.69. Under the same processing conditions, only dynamic recovery occurred in the non-porous (bulk) aluminum. It is found that bulk forming of metallic foam could be a process for grain refinement.

In chapter 4, compression behavior of metallic foams was investigated. Typical stress-strain curves show an elastic region at the first step, followed by a plateau region with a constant flow stress. After the plateau region, the foam is densified with sharp increase in stress. Repeated compression test of open-cell type nickel foam was conducted to reveal porosity change and to derive constitutive equation for prediction of deformation and density. The compression test was conducted with two types of cylindrical foam billets which are different in

mean pore diameter (d_{pore}: 0.8 mm and 3.2 mm). Nominal stress of the open-cell foam gradually increases until the strain of 0.4, after that stress increases parabolically. Plateau region was not clearly observed with the open-cell foam. The apparent density and diameter of the foam with 0.8 mm in mean pore diameter shows little increase until the nominal strain of 0.4 (density: 0.423 to 0.681 Mg/m^3). After the strain of 0.4, the density rapidly increases with increase in diameter of the billet to 2.69 Mg/m^3. The equation for change in radial strain and relative density was derived based on Oyane's equation considering volume change. The radial strain increment increases with decrease in porosity.

In chapter 5, repeated compression test of closed-cell type aluminum foam was also conducted to investigate deformation behavior. Plateau region was clearly observed. In the plateau region (nominal strain: ~ 0.5), the apparent density gradually increases from 0.287 Mg/m^3 to 0.523 Mg/m^3 with little increase in diameter of billets. After the plateau region, the density rapidly increases to 0.796 Mg/m^3 with increase in diameter to 10.52 mm.

In chapter 6, Changes in radial strain and compressive stress of open-cell and closed-cell foams was predicted by the constitutive equation. Even though the pore structures are different, the radial strain increments of open-cell foam and closed-cell foam are similar if the porosity is same. Appropriate material constants ($a = 3/\sqrt{2}, m = 0.3$) for the constitutive equation based on Oyane's yield criterion, were derived. Changes in density, stress and diameter of billets were predicted. Even though pore structures are different, deformation behaviors of metallic foams are predicted successfully by the constitutive equation with same constants.

In chapter 7, applications of metallic foams in bulk metal forming are described.

Through this study, deformation behavior of metallic foams in bulk forming processes is made clear. Changes in dimensions and flow stress are described with density change. Deformation, flow stress and density are predicted with a constitutive equation. In addition, formation of fine-grained microstructure is found in metallic foams after bulk forming. Therefore, this thesis contributes establishment of bulk forming technology of metallic foams and their industrial applications.

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論文審査の結果の要旨及び担当者

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論文審査の結果の要旨

発泡金属は，内部に多数の気孔を有する低密度の金属で，軽量性，高エネルギー吸収性，遮熱性などの観点から注目を集めている．しかしながら，低強度であること，機械加工や接合が困難であることから構造材料としての工業的応用は限られている．発泡金属の塑性加工は，気孔を閉塞させ軽量性が失われる欠点があるものの，応用に適した複雑形状への成形，加工硬化による強度の改善，気孔形態や微視組織の制御などの点では利点が期待できる．しかしながら，発泡金属のバルク加工は大きな体積変化をともなうためその変形挙動は必ずしも明らかにされておらず，加工技術も確立されていない．本論文は，発泡金属のバルク加工における変形挙動について研究を行った成果をまとめたものであり，得られた主な知見は以下の通りである．

1. アルミニウム管でシースされたクローズドセル型発泡アルミニウムの冷間押出し特性を解明した．加工初期ではストロークとともに荷重は徐々に増加し，発泡アルミニウムが十分に圧密化された後に，高荷重でダイスからの押出しが行われ，その後荷重が漸減するという発泡金属に特有の押出し特性を見出した．このとき，押出し比が大きいほど，押出し材の密度のみならずダイスからの押出し時の密度も大きいこともあわせて見出した．
2. 発泡アルミニウムに冷間押出しを行って得られた緻密体に，さらに強ひずみ加工として大圧下異周速圧延を適用して微視組織の観察を行い，従来プロセスよりも大角粒界の割合の大きい微細粒組織が得られることを見出し，気孔の圧着時に大角粒界が形成されるという機構を提案した．
3. クローズドセル型発泡アルミニウムおよびオープンセル型発泡ニッケルの円柱状試験片の圧縮特性を，繰り返し圧縮法を採用することで密度変化と対応づけて調査している．その結果，ひずみ 0.4 以下における変形は体積変化が主体で直径変化を無視しうること，ひずみ 0.4 以上では直径変化が大きいことを見出した．そして，金属粉末の圧粉焼結体に対して提案された大矢根の降伏条件と連合流れ則を用いることで，これらの発泡金属の密度変化と変形挙動を関連付けて記述できることを見出した．

以上のように，本研究はバルク加工における発泡金属の変形挙動，組織変化，加工特性を解明したものであり，発泡金属の加工技術の確立および工業的利用の拡大に寄与できる新たな知見を多数含んでおり，材料工学分野の発展に貢献するところが大きい．よって，本論文は学位論文として価値あるものと認める．