Some Aspects on Cold Deformation Characteristics of Sintered Fe-0.8%C-1%Si-0.4%Cu Steel Preforms

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Abstract. Cold upsetting experiments were carried out on sintered Fe-0.8%C-1.0%Si-0.4%Cu preforms to evaluate their deformation characteristics. The sintered preforms are subjected to axial compressive deformation under nil and graphite lubricant condition in steps of 0.04 *MN* until cracks began to appear on the free surfaces. Combined strain, $e^{\varepsilon_z-\varepsilon_\theta}$ has been considered to study the densification mechanism of the preforms. It was observed that overall, densification enhances against combined strain for both the friction conditions, however dry friction restricts the free deformation consequently facilitates faster densification as compared to its counterpart. Further, an attempt has been made to analyse various stresses against strain as well as against attained density. The calculation for Poisson's ratio has been shown and its characteristics have been detailed against attained density.

Introduction

Cold upsetting processes involves fabrication of a preform by conventional powder metallurgy P/M route (pressing and sintering), followed by the conventional forging [1]. In general, the preform produced by this processes will undergo large degree of plastic deformation with enhanced level of densification [2] (i.e., up to near net shape). The non-uniform deformation in the presence of frictional forces results in the existence of secondary tensile stresses in the circumferential direction accompanying the axial compressive stresses [3]. Since the primary cause of the fracture in upsetting is tensile stresses, it is therefore essential to investigate fracture during the deformation processing of sintered powder materials with the help of axial upsetting tests. It is well established that the Poisson's ratio for the P/M materials under plastic deformation is less than 0.5 and only approaching to 0.5 in the near vicinity of the theoretical density [4]. This is due to volume change occurs as a result of pore closure during deformation. Thus a mass constancy principle is adopted to establish fracture criterion for P/M material.

The present investigation is aimed at evaluating the deformation behaviour of Fe-0.8%C-1.0%Si-0.4%Cu sintered steel preforms during the cold upsetting test because of the industrial importance attached to the aforesaid material. An attempt has been made to investigate the influence of frictional conditions during cold upsetting of constant initial fractional theoretical density (0.86) and initial heights – to – diameter ratio (aspect ratio) of 0.40. Also, an attempt is made to establish the relationship between the fractional theoretical density, the Poisson's ratio and other parameters namely, the stress, strain and strain factor. The deformation study helps to understand the formability nature of under cold upsetting on the given conditions, consequently used in design of preform.

Experimental Details

Atomized iron powder of -150 μm size and silicon & copper powder of -37 μm size of each and the graphite powder of 2-3 μm size has been utilized to prepare the preform. Chemical analysis indicated that the purity of iron, copper and silicon powders were 99.7%, 99.93% and 99.90% respectively and the rest were insoluble impurities. The apparent density (*g/cc*), flow rate (*s*) per

100 *g* and compressibility (*g/cc*) at pressure of 430±10 *MPa* for Fe and Fe-0.8%C-1.0%Si-0.4%Cu blend are 2.96 & 2.89; 56 & 49.2; and 6.55 & 6.55 respectively. The required amount of powders corresponding to composition were measured and blended in a pot mill along with porcelain balls of ratio 1:1 by weight for a period of 20 *h* in order to obtain homogenous mix. This powder blend was compacted on a 1.0 *MN* hydraulic press in the pressure range of 430±10 *MPa* to obtain an initial fractional theoretical density of 0.86±0.01. The compacts were sintered in an electric muffle furnace at $1150^0 \pm 10^0$ *C* for 90 minutes followed by furnace cooled. To avoid oxidation during sintering, the compacts were ceramic coated.

Sintered preforms were machined to yield the initial aspect ratios of 0.40. Initial dimensions of sintered preforms like their heights and diameters were measured and recorded. Each specimen was axially deformed on a flat die set in the increment loading step of 0.04 *MN* under dry or unlubricated dies and graphite employed friction conditions respectively till cracks appear on its free surface. Immediately after completion of each step of loading, the height, the contact diameters (at the top and bottom), the bulged diameter and the density were measured for each of the deformed compacts. The density measurements being carried using the Archimedes principle. Experimental measurements were also used to calculate various parameters namely stresses, Poisson's ratio and the strains.

Theoretical Analysis

The present investigation is based on the analytical determination of the deformed density (fractional theoretical density), strains, stresses, and the plastic Poisson's ratio. The material under consideration is porous in nature, thus the expression between relative density and combined strain can be expressed as explained elsewhere [5]:

$$\left(\frac{\rho_f}{\rho_{th}}\right) = \left(\frac{\rho_0}{\rho_{th}}\right) e^{\varepsilon_z - \varepsilon_\theta} . \tag{1}$$

where, ε_z is height strain and is given by

$$\varepsilon_z = \ln\left(h_0 / h_f\right). \tag{2}$$

and, ε_θ is hoop strain based on contact and bulged diameter can be written as,

$$\varepsilon_\theta = \ln\left(\left(2D_b^2 + D_c^2\right)/3D_0^2\right). \tag{3}$$

However, the conventional hoop strain ($\varepsilon_{c\theta}$) can be calculated as, $\varepsilon_{c\theta} = \ln\left(D_c / D_0\right)$; where, D_0 is the initial diameter of the preform before deformation; D_b is the bulged diameter preform after deformation; D_c is the contact diameter of the preform after deformation; h_0 is the initial height of the cylindrical preform before deformation; h_f is the height of the preform after deformation; ρ_0 is the initial preform density of the cylinder; ρ_f is the density of the preform after deformation; and ρ_{th} is the theoretical density of the fully dense material.

Since the ratio (ρ_0/ρ_{th}) is taken as constant, Eq. 1 shows an exponential relationship between the density ratio (ρ_f/ρ_{th}) and the difference between the two true strain ε_z and ε_θ. Now, defining a new or instantaneous Poisson's ratio (ψ) based on the contact and bulged diameter as given below:

$$\psi = \frac{\varepsilon_\theta}{2\varepsilon_z} . \tag{4}$$

enables Eq. 4 to be written as :

$$\psi = \ln\left(\frac{2D_b^2 + D_c^2}{3D_0^2}\right) \Big/ \ln\left(\frac{h_0^2}{h_f^2}\right). \tag{5}$$

It is described elsewhere [6] that the expression for hoop stress can be determined as,

$$\sigma_\theta = \left(\frac{\alpha + \nu}{1 + \alpha\,\nu}\right)\sigma_z. \tag{6}$$

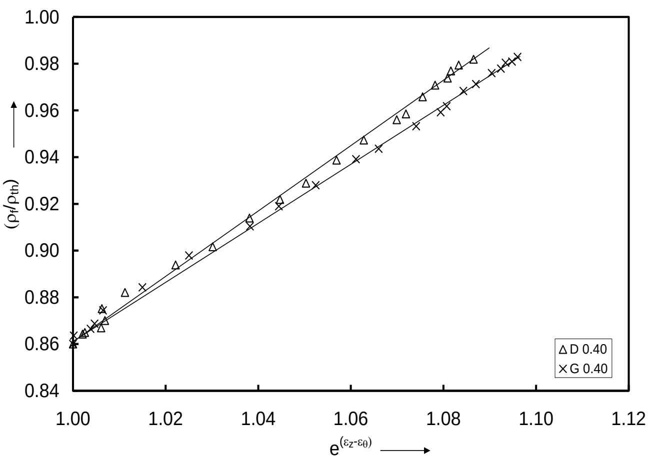
where, $\alpha = (d\varepsilon_\theta / d\varepsilon_z)$, and $\nu = (\varepsilon_{c\theta}/\varepsilon_z)$, conventional Poisson' ratio. Now substituting the value for the true axial stress, σ_z, the true hoop stress, σ_θ, can be calculated, where, σ_z = load / contact surface area. Further, using the values of σ_z and σ_θ, the hydrostatic stress (σ_m) can be calculated using the relationship given below:

$$\sigma_m = \left(\frac{\sigma_z + \sigma_\theta}{3}\right). \tag{7}$$

Results and Discussion

To establish a relationship between the fractional theoretical density (ρ_f/ρ_{th}) of the deforming preform and the value of $e^{\varepsilon_z - \varepsilon_\theta}$ in accordance with the theoretically derived relationship (Eq. 1) for sintered P/M preforms during cold upsetting deformation, a plot has been constructed and is shown in Fig. 1. This shows a power law relationship between the fractional theoretical density and $e^{\varepsilon_z - \varepsilon_\theta}$ with the slope of 1.4 and 1.25 respectively for the preform deformed under dry and graphite friction condition. This exhibits that the rate of densification attained by preform deformed under nil lubricant is high in comparison with its counterpart. Most of the fractional theoretical density values at very initial stage fall very closely and there are no much clear evidence of frictional effect. This is due due to the initial resistance of the preform against deformation, that is, the initial steps of load may not sufficient to collapse or dislocate the particles. However on further continuation of deformation confirms the effect of friction; such as the dry friction condition improves density over graphite employed condition. In general, the characteristics nature between densification and combined strain show an increasing trend for both the friction conditions.

The stresses, namely, the axial (σ_z) the hoop (σ_θ) and the hydrostatic (σ_m) increase with the increasing level of axial strains (ε_z), as revealed from Fig. 2. The hoop stress is tensile in nature because during compressive loading the bulge diameter expands. However, for any deformation level, the increase in hoop stress due to loading is very low compared to that of the axial stress. On the other hand it is observed that the value of the hydrostatic stress is much less than the other stresses, namely, axial and hoop stress and it is also compressive in nature. Further it is interesting to note that the influence of lubricants is evident in hoop and axial stress, which is not the case for hydrostatic stress and it exhibits virtually nil difference. This ensures that irrespective of level and media of deformation the existence of mean stress is equal in magnitude. To elaborate more on the behaviour of axial stress with respect to axial strain, it can be observed that effect of frictional constraints is quite dominant in the later stages than in the initial stages of deformation. It is found that a preform deformed under dry friction condition exhibits improved load bearing capacity compared to lubricant employed condition, subject to the condition that the composition, initial preform density, and initial aspect ratio is kept constant. In addition, it can be observed that the graphite lubricant facilitated substantial deformation both in axial as well as lateral direction without fracture at free surfaces in comparison to dry friction condition.



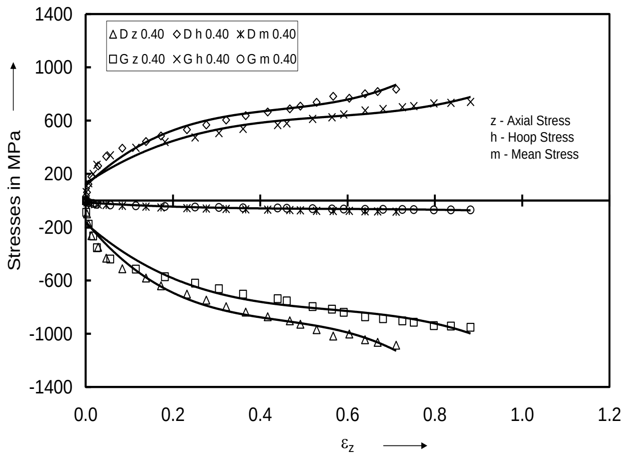


Fig. 1 The relationship between (ρ_f/ρ_{th}) and $e^{\varepsilon_z-\varepsilon_\theta}$

Fig. 2 Plot between various stresses and ε_z

The relationship between the Poisson's ratio and the percent fractional theoretical density achieved during cold upset forming is shown in Fig. 3. The characteristic features of these curves can be classified into three distinct categories. Category I describes a rapid rise in the values of Poisson's ratio with little densification, which means that the material offers initial resistance to deformation, as a consequence of which the preform undergoes more of a lateral deformation than that of a height strain (both being negligibly small). Category II is treated as a steady – state condition, where most of the densification occurs with a small increase in Poisson's ratio. In this stage, densification occurs mostly in the lateral direction without much pronouncement in lateral strain. Category III involves the stage where a rapid increase in Poisson's ratio occurred without much enhancement in the density values in the deforming preforms. In this region, the lateral spread is greater compared to the height strains. However, the tendency is to approach a limiting value of 0.5, which is theoretically feasible value of Poisson's ratio [7].

Further, Fig. 3 shows that the variation of Poisson's ratio calculated: (i) Based only on the contact diameter (D_c), conventional; and (ii) Based on both the contact and the bulged diameters (D_c & D_b), instantaneous; with respect to the percent fractional theoretical density, for the aspect ratio of 0.40. It is found that for any given frictional conditions and the theoretical density values, the values of instantaneous Poisson's ratio obtained based on both contact and bulged diameter is greater than that obtained based on only contact diameter. The difference between these two values of Poisson's ratio is considerably evident when the fractional theoretical density values are less. However, as the fractional theoretical density value approaches the theoretical value, the above difference become negligible. Similar is the condition at initial stage, this is due to the preform density taken as constant.

To demonstrate the relationship between the axial stress, σ_z, and the percentage theoretical density, $\%(\rho_f/\rho_{th})$, a plot has been constructed and is shown in Fig. 4. It also exhibits the effect of frictional conditions on the aforesaid relationship. General observation reveals a rapid increase of stress in the initial stage of densification, thereafter stress continue to raise, but at a lesser rate. It is noted that the increase in axial stress being complimented by the work hardening phenomena during densification/deformation. It is well established that the hardening in P/M material during cold upsetting is due to matrix and geometric [8]. Further, it is observed that the preform deformed under dry friction condition exhibits higher stresses for any attained density than that of the preform deformed under graphite condition.

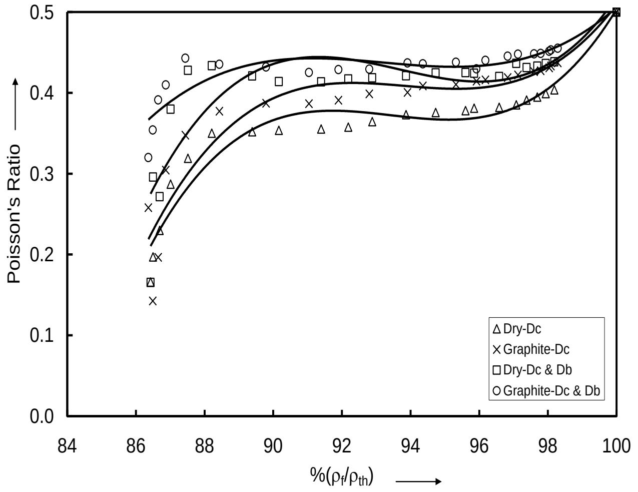


Fig. 3 Plot between Poisson’s ratio and *%(ρ_f/ρ_{th})*

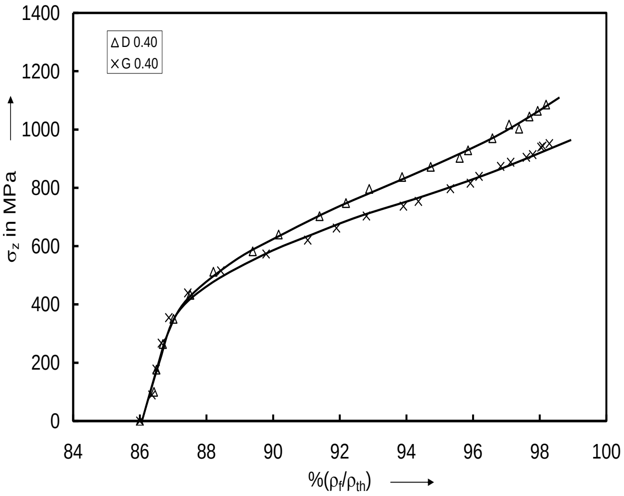


Fig. 4 Plot between σ_z and *%(ρ_f/ρ_{th})*

Conclusions

An empirical relationship has been obtained between fractional theoretical density and combined strain, which is found to obey for all the friction conditions. In general, stresses found to have an increasing trend against strain induced, except for mean stress, which is almost constant throughout deformation. The Poisson’s ratio, calculated with respect to contact diameters and with respect to contact and bulge diameters show a similar characteristics nature. Although differences between them are profound at the initial stage of densification, converge at near theoretical density and approaching to theoretical Poisson’s ratio value of 0.5.

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