Fracturing and Deformation Characteristics of Aluminium Preform during Cold Forging at Low Strain Rates

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Abstract: The industrial processing of sintered powder preform has been developed for manufacturing various engineering components. The present investigation has been undertaken to analyze the deformation characteristics during the cold forging of sintered aluminium preform at low strain rates. Experiments have been conducted and measurements made on deformation during cold forging on aluminium preforms with lubricated end conditions. Experimentally obtained flow load and plastic work done are in good agreement with theoretical estimates.

Keywords— Sintered powder preform, deformation characteristics, flow stress, plastic work done

I. Introduction

The forging of metal powder preform has aroused considerable interest in recent years, the technique combining some of the best features of two well established technologies, namely powder metallurgy and forging. Cull (1970) [i] has cited the advantages of metal powder preform forging associated with conventional powder metallurgy processes along with additional strength provided by the elimination of porosity by forging. The mechanical and metallurgical properties of metal powder components compare favorably with those of wrought materials. Jones (1970) [ii] had pointed out technical and economical advantages of sintered forged powder products.

Green (1971) [iii], had carried extensive investigations during compression of metal powders and established the plasticity upper-bound and slip-line field theories for sintered powder materials. Tabata and Masaki (1978) [iv] studied the plastic yield behavior of porous metals and proposed the principal strain increments, volumetric strain increments and corresponding yield criterion for powder metallurgy materials. Ramakrishnan (1980) [v] had conducted basic experiments of preform forging. Jha and Kumar (1988) [vi] carried out experimental investigations to analysis pressure distribution on die preform interface and die load during axi-symmetric cold forging of sintered Iron powder preforms and plain strain forging of copper powder strips.

Singh and Jha (2001) [vii] have analyzed the dynamic effects during high speed forging of sintered preforms by energy method for axisymmetric and plain strain conditions. They have shown that die velocity has significant effect on deformation characteristics. Ranjan and Kumar (2004) [viii] presented a generalized solution to determine die pressure for high speed forging of N-sided polygonal sintered powder disc. Sumathi and Selvakumar (2012) [ix] have investigated the workability of sintered copper-silicon carbide preforms during cold axial upsetting. They showed that strength property is very high at 5 % of SiC with copper and the initiation of crack appeared at a low axial strain with higher value of SiC addition. Verma   *et.al* (2013) [x] have investigated the deformation characteristics during open-die forging of silicon carbide particulate reinforced aluminum metal matrix composites (Si-Cp AMC) at cold conditions. Authors have not yet come across the investigations in which the effect of strain rate on the preform has been taken into consideration, as the strain rate is one of the most important parameter in forging process.

The present paper reports an investigation into forging of sintered aluminium cylindrical preforms at different strain rates. The appropriateness of the theoretical results obtained is verified experimentally and discussed to explain the interaction of the various processing parameters involved. It is expected that these investigations will be helpful in understanding of the deformation loads work done required during deformation of metal powder preform at different strain rates.

II. Theory and Methodology

Yield Criterion for Plastic Deformation of Sintered Metal Powder Preforms

During sinter forging of the metal powder preform changes in volume occurs due to porosity. The following assumptions are made in the analysis.

The material of the preform is inhomogeneous and isotropic rigid plastic but compressible. The volume inconstancy is assumed in the compatibility equations, as change in volume occurs due to compaction of pores during forging.

The density distribution is non-uniform throughout the deforming preform. Both sliding (areas of low density) and sticking friction (areas of high density) are considered.

The yielding of sintered material is sensitive to hydrostatic stress.

The deformation is inhomogeneous and barreling is considered.

The friction due to adhesion (sticking friction) is a function of relative density ρ_r.

Tabata and Masaki [v] proposed the following yield criterion for sintered performs as

$$\rho^k \sigma_o = \sqrt{3J_2^{/} } \pm 3\eta\sigma_m \qquad (1)$$

where negative sign is for compressive load and $\eta \leq 0$ and the values of η and k are determined experimentally as:

$$\eta = 0.54(1 - \rho)^{1.2} \qquad \text{for } \sigma_m \leq 0 \qquad (2)$$

For axisymmetric conditions the equation (2), reduces to

$$\sigma_1 = \frac{\rho^k \sigma_o}{(1-2\eta)} + \frac{(1+\eta)}{(1-2\eta)}\sigma_2 \qquad (3)$$

The moment yielding starts the above equation further reduces to give flow stress as

$$\lambda = \frac{\rho^k \sigma_o}{(1-2\eta)} \qquad (4)$$

According to Tabata and Masaki the principal strain increments are given as

$$d\varepsilon_i = d\lambda\left[\frac{3(\sigma_i - \sigma_m)}{2\sqrt{3J_2'}} \pm \eta\right], \quad \text{(for i = 1, 2, 3)} \qquad (5)$$

where

$d\lambda = \frac{\sqrt{2}}{3}\sqrt{(d\varepsilon_1 - d\varepsilon_2)^2 + (d\varepsilon_2 - d\varepsilon_3)^2 + (d\varepsilon_3 - d\varepsilon_1)^2}$ a positive constant, the volumetric strain increment $d\varepsilon_v$ is given as

$$d\varepsilon_v = d\varepsilon_1 + d\varepsilon_2 + d\varepsilon_3 = \pm 3\eta d\lambda = \pm\mu\sqrt{2}\eta[(d\varepsilon_1 - d\varepsilon2)2 + (d\varepsilon2 - d\varepsilon3)2 + (d\varepsilon3 - d\varepsilon1)2]12$$
(6)

For axisymmetric compression condition it yields the compatibility equation as

$$\varepsilon_r = \frac{(2\eta - 1)}{2(\eta + 1)}\ln\frac{h_2}{h_1} \qquad (7)$$

The plastic work done per unit volume is given by

$$dW_p = \sigma_1 d\varepsilon_1 + \sigma_2 d\varepsilon_2 + \sigma_3 d\varepsilon_3 \qquad (8)$$

Substituting equation (6) in equation (9) and solving one leads to

$$dW_p = \frac{\sqrt{2}}{3}\rho^k \sigma_0\sqrt{(d\varepsilon_1 - d\varepsilon_2)^2 + (d\varepsilon_2 - d\varepsilon_3)^2 + (d\varepsilon_3 - d\varepsilon_1)^2} \quad (9)$$

On solving, the above equation reduces and gives the plastic work done per unit volume for axisymmetric compression as

$$W_p = \frac{2}{3}\rho^k \sigma_0\left[\frac{(2\eta - 1)}{2(\eta + 1)} - 1\right]\ln\frac{h_2}{h_1} \qquad (10)$$

The total work done (elastic and plastic) per unit volume is

$$W_{\text{Total}} = W_{\text{elastic}} + W_p \qquad (11)$$

$$W_{\text{Total}} = \sigma_o \times \% \text{ reduction} + W_p \qquad (12)$$

Sinter-Forging of Aluminium Preforms

The used metal powder was supplied by M/s Qualikem Fine Chemicals Pvt. Ltd. Delhi, India figure 1. The cylindrical preforms were fabricated from aluminium powder using a closed cavity circular die-set of 20 mm diameter as shown in figure 2, on 400 kN UTM at a compaction pressure of 300 MPa and were sintered at 500° C in microprocessor controlled muffle furnace. In order to minimize non-uniformity of the density distribution, the compacts were wrapped in Teflon sheets (acting as lubricants) and were re-pressed at same compaction pressure in the same die and then re-sintered at the same temperature and the time. The surfaces of specimen were than polished with the fine emery paper. The preform density was obtained simply by measuring dimensions and weight then the relative density of the preform was obtained.

Fig. 1 Prepared preform and used metal powder

Fig. 2 Die set to fabricate cylindrical preform

In order to confirm the validation the theoretical estimates of flow stress, plastic work done, the stored strain energy of the sintered perform and to analysis its fracture mechanism, the cold forging of the sintered Al preform of aspect ratio 1.25 was done on 400 kN computerized UTM by selecting strain rates as 1.5 mm/ min, 2 mm/ min, 2.5 mm/ min and 3mm/ min for lubricated end conditions. Firstly, two preforms were compressed up to 60% and 40% of the height of the preform. It was observed that the cracks appeared on the equatorial surfaces at about 30% reduction in height approximately. Subsequently, for each strain rate setting five specimens were compressed form a height of 25 mm to 18 mm approximately i.e. 25% reduction in height. The UTM computer stored the results in the form of excel-sheet: the applied load in kN, cross head travel in mm and time in a step of 0.1 second.

III. **Results and Tables**

Ascertainment of flow stresses and comparison with theoretical estimates

The density and Modulus of Elasticity of aluminum had been considered as 2.7 gm/cm^3 and 70 GPa. Considering the strain value of 0.15% the flow stress of aluminum was calculated as σ_o=70 x 0.0015 GPa i.e. 105 MPa. Knowing the relative density of the preform the flow stress had been calculated as per the equation (4). Experimentally and theoretical values of flow stresses are given in table 1.

Table 1 Comparison between the Calculated and Experimentally obtained values of flow stresses

Sr. No	Strain rate	Flow stress		Relative difference
		Calculate	Experimental	
	mm/min	MPa	MPa	%
1	1.5	85.3	86.03	-0.81
2	1.5	86.64	82.64	4.47
3	1.5	84.78	73.28	13.56
4	2	86.51	84.42	2.41
5	2	84.03	81.66	2.82
6	2	83.28	84.75	-1.769
7	2.5	85.04	78.92	7.19
8	2.5	84.22	81.24	3.53
9	2.5	87.41	65.55	25.00
10	3	85.47	89.38	-4.58
11	3	83.98	82.37	1.91
12	3	83.33	78.19	6.22

Ascertainment of total work-done and comparison with theoretical estimates;

The stress- strain curves are plotted from the obtained experimental results and the plastic work done "W_p" at 20 % reduction in height was determined by finding out the area under the stress strain-curve using Met-lab software. Table 2 shows the theoretical and experimentally obtained values of total work done (including plastic) per unit volume as per equation (12). The relative difference between both the values is very small.

Table 2 Comparison between the Theoretical and Experimentally obtained values of Work-done

Sr. No.	Strain rate	Work done W$_{Total}$		Relative difference
		Calculated	Experimental	
	mm/min	MPa	MPa	%
1	1.5	25.32	25.71	-1.55
2	1.5	25.65	25.32	1.29
3	1.5	25.5	25.41	0.353
4	2	25.98	26.06	-0.16
5	2	25.21	24.45	3.0
6	2	26.1	24.95	4.41
7	2.5	14.1	23.99	0.453
8	2.5	26.3	26.36	-0.213
9	2.5	25.8	25.61	0.736
10	3	26.1	26.74	-2.463
11	3	25.00	24.49	2.041
12	3	25.4	25.31	0.354

Fracture mechanism of metal powder preforms

From the experimental observations the values of the stress rate and strain rate were calculated as:

$$\text{Eng. Stress rate} = \frac{\Delta \sigma_e}{\Delta t} = \frac{\text{stress at } t_n - \text{stress at } t_{n-1}}{t_n - t_{n-1}} \qquad (13)$$

$$\text{Eng. Strain rate} = \frac{\Delta \varepsilon_e}{\Delta t} = \frac{\text{strain at } t_n - \text{strain at } t_{n-1}}{t_n - t_{n-1}} \qquad (14)$$

These values were plotted on time scale to analyze fracture mechanism of the compressed preform. The graph plotted between stress rate and deformation time (Fig. 3) showed a high peak value of stress rate just before reaching to the plastic stage. Similarly, the graph plotted between strain rate and deformation time ((Fig. 4) showed a high peak value of strain rate also just after the deformation started. High compression energy is required to close down the pores and for notch propagation of the preform during compression. Once the notch propagation starts the stress rate comes down to an average of 4 MPa/second for the considered preform. This phenomenon is happening just before it reaches to plastic deformation. Similarly strain rate value reaches to a peak value of 0.016 mm/second and this comes down to 0.004mm/second. This phenomenon is just after the plastic deformation started and notch propagation and formation continued. Thus, during forging of metal powder preform, the compaction (densification) and the compression both take place simultaneously. Initially larger amount of applied load is consumed in densification and lesser amount is utilized for compression. Brake down of the initially weak structure takes place and is subsequently reorganized into a highly oriented strong material and after attaining ρ≈1 the preform starts yielding significantly.
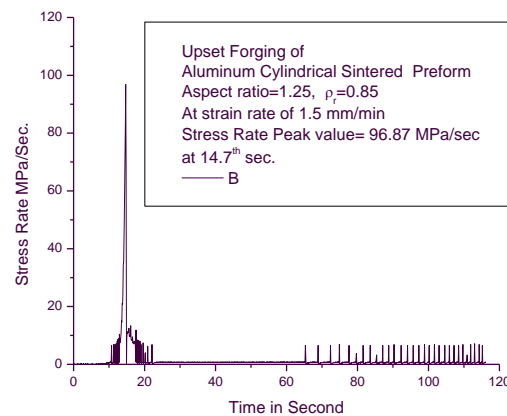

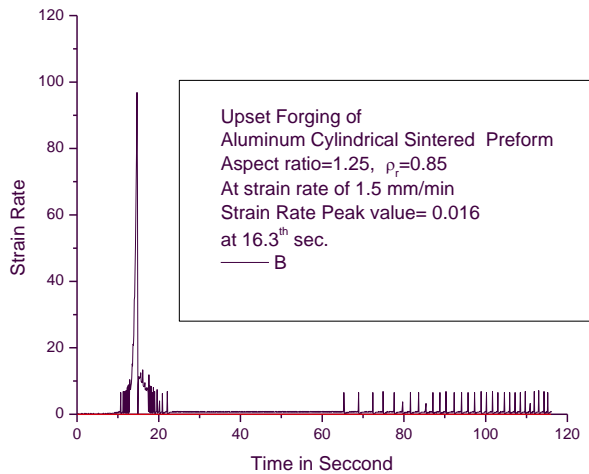Fig. 3 Variation of stress rate with time during deformation of the preform

Fig. 4 Variation of strain rate with time during deformation of the preform

Figure 5 illustrates the effect of various stresses on pore shape in metal powder performs. Compressive stresses will gradually close the pores and the relative density will increase, whereas tensile stresses will cause an increase of pore size and the relative density will decrease. With the application of compressive stresses the pores gradually close, although some pores finally open at the free surface and produce cracks (Fig. 5 a). Tensile stresses produce equiaxed pores (Fig. 5 b), whereas pure shear stress generate elongated pores in the shearing direction. The pores point in opposite directions on the two fracture surfaces (Fig. 5 c). The non uniform stresses associated with tearing produce elongated dimples on both fracture surface that point back to crack origin (Fig. 5 d).
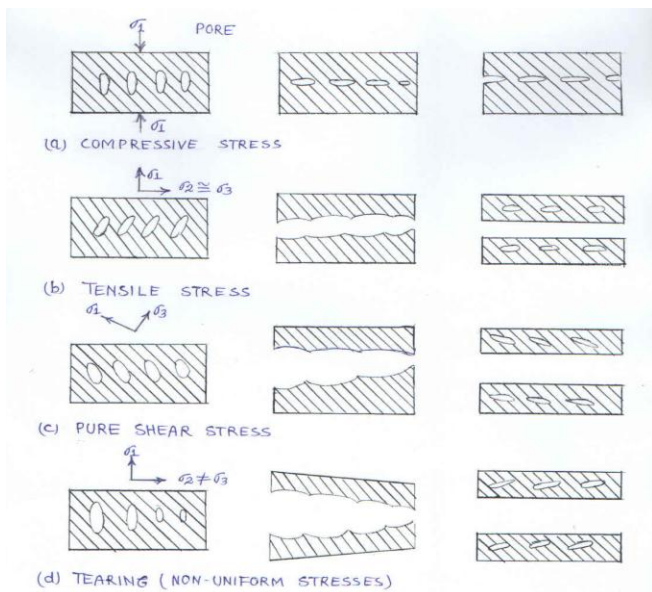

Fig. 5 Effect of various stresses on the pores of metal powder preform

IV. Conclusion

The obtained values of flow stresses during forging of the preform at low strain rates are in very much close agreement with the results obtained from theoretical model. The value of work done obtained from area under stress-strain curves using Met-lab at 20% deformation. are also in agreement with the theory. During forging a high peak value of stress rate is observed just before reaching to the plastic stage and a high peak value of strain rate also is observed just after the deformation started.

Notations

ρ	relative density of the preform
λ	flow stress of the metal powder preform
k	constant equal to 2 in the yield criterion
η	function of relative density of preform
$d\lambda$	a positive constant
p	pressure
$\sigma_1, \sigma_2, \sigma_3$	principal stresses
$d\varepsilon_1, d\varepsilon_2, d\varepsilon_3,$	principal-strain increments
h	instantaneous thickness of the work piece
σ_0	yield stress of the non-work-hardening matrix metal
σ_m	hydrostatic stress
J'_2	second invariant of the deviatoric stress
W_p	plastic work

Subscripts

1. initial condition
2. **final condition**

Acknowledgement

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