Phenomenon of Strain Hardening in Sintered High Carbon Steel Preforms during Cold Upsetting

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Abstract

Present investigation pertains to evaluate strain hardening characteristics of Fe-0.8%C sintered preforms during cold upsetting. Preform density and deformation media were kept constant, however, two different heights to diameter ratio were considered for the analysis, which follows 0.40 and 0.75. The elemental powders were taken in a weight proportion to satisfy the composition considered, which were subjected to primary operations of powder metallurgy to get 86% initial density. The sintered preforms were further cold deformed in between the mirror polished flat dies under dry friction condition at a fixed step of loading till crack appears on the free surfaces of deforming preforms using hydraulic press of 1.0MN capacity. Experimental results revealed the fact that the variation of stresses with respect to the strain and/or density is of three different stages. The first and third stage established high resistance against deformation, however on the intermediate stage, dislocations of particles were found to be high, which enabled to get high densification. Further the study is concentrated to establish the strain hardening behaviour, which revealed that the lower heights to diameter ratio (0.40) is hardened at faster in the later stage as compared to its counter part.

Keywords: Cold upsetting; heights-to-diameter ratio; strain hardening characteristics.

1.0 INTRODUCTION

The sintered powder metallurgy (P/M) products cannot be employed in structural applications as, they contain fairly good percentages of porosities. These substantial amount of pores being present in the P/M materials render them mechanically weak, since they exhibit low yield strength, low ultimate tensile strength and fracture strength, low percentages of area reduction and elongations, thus, making the P/M materials differing from the conventionally fully dense materials [1-3]. Pores present in a porous material act as the sites of stress raisers and stress concentrators resulting in crack initiation and its propagation. Forming powder preforms to desired shapes with high level of densities had been the endeavors of the investigators in the past [4-7], but, 100% dense components could not be produced. However, enhancing the density of porous materials through eliminating the pores by continuing the deformation can enhance mechanical properties. Densification can be significantly enhanced through the secondary deforming operations, namely, powder preform forging, powder rolling, powder extrusion etc., [8,9]. In general, the powder preform forging processes have been used in the production of large number of automotive and non-automotive components [10]. Basically two distinct modes of powder preform forgings are carried out. One involves compression without giving any room for inducing any changes in the cross-section called as the repressing mode and other one involving compression of relatively simple shaped preforms into a complex product called as true forging. The former part of the argument involves densification with no lateral deformation while the later part involves densification as well as the shape changes occurring simultaneously through large degree of plastic deformations coupled with an extended level of lateral flow of material [9,11,12].

The frictional forces developed between the workpiece and the forming tools are very essential to be considered for any of the metal working processes [13]. During the cold axial upset forming, heterogeneity in deformation is observed due to the existence of frictional constraints in between the workpiece and top & bottom dies. Just beneath the faces of the flat dies, which are in contact within the workpiece, a conical wedge shaped relatively undeformed material is formed. But, the remaining materials tend to flow easily towards the nearest free surfaces where the resistance to metal flow is minimum [14]. Therefore, in cold upset forming, barreling become predominant in absence of the lubrication. However, the detrimental effects of friction can be minimized by the application of proper lubricants. Also, benefits that can be derived by using lubricants are the reduction in barreling, improvement in surface finish, decrease in wear and tear of the tooling [15,16]. Densification process is therefore, can be perceived as a combination of pore filling and vacancy destruction processes. However, the densification of the preforms by plastic deformation is strongly influenced by the stress state created in the material by the application of external loads. Thus, the present investigation is aimed to investigate the relationship that existing between the applied stresses against the induced height strain and the density attained during cold deformation of sintered Fe-0.8%C preforms with the influence of two different preform geometries. Further, extended to study the strain hardening characteristic of the selected material.

2.0 EXPERIMENTAL DETAILS

2.1 Material Characterisation

Atomized iron powder of -150µm size was procured from M/S Sundaram Fasteners Ltd., Hyderabad, India and the graphite powder of 2 – 3 µm was supplied by the Ashburry Graphite Mills Inc., Ashburry Warren County, New Jersy, USA. Analysis for the purity of iron powder was found to be 99.7% and impurity of 0.3%. Characterization of iron powder and the powder blend corresponding to the Fe-0.8%C steel composition was carried out. The properties were presented in Table 1.

Table 1: Characterization of Iron Powder and Fe-0.8%C Blend

Si. No.	Property	Iron powder and Powder blend	
		Iron	Fe-0.8%C
1.	Apparent Density (g/cc)	2.96	2.87
2.	Flow rate, (s/100g) by Hall Flow Meter	56.0	54.0
3.	Compressibility (g/cc) at pressure of 430±10MPa	6.55	6.50

4. Sieve size analysis of iron powder

Sieve size (µm)	150	+126	+106	+90	+75	+63	+53	+45	+37	-37
Wt % Ret.	10.14	21.90	9.46	2.02	20.10	12.10	11.10	5.70	0.31	7.00

2.2 Primary operations of P/M

The required amount of powders in weight percent corresponding to Fe-0.8%C were taken and blended in a pot mill along with porcelain balls of ratio 1:1 by weight for a period of 20 hrs in order to obtain homogeneous mix. This powder blend were compacted on a 1.0MN capacity hydraulic press in the pressure range of 430±10Mpa to maintain the constant initial fractional theoretical density of 0.86±0.01, followed by sintering operation carried out using electric muffle furnace at temperature range of $1150^0 \pm 10^0$C and maintained for a period of 90 minutes. In order to avoid from oxidation during sintering the compacts were ceramic coated. These sintered preforms were allowed to cool inside the furnace itself till they attained ambient condition.

2.3 Cold Upsetting

Sintered preforms were machined to such a dimension so as to provide the preforms of constant initial height-to-diameter ratio (aspect ratio) of 0.40 and 0.75 respectively. Initial density measurements were carried out through calculation using geometries. All dimensional measurements were carried out by using digital vernier calipers and the weight or mass of preforms were found out by single pan electronic balance of model AD-180 of the least count of 0.0001g. Preforms of Fe-0.8%C were axially deformed on a flat die set in the incremental loading step of 0.04MN each under nil/no lubricating constraint until visible surface cracks appear on the deforming preforms. Dimensional measurements such as deformed height, deformed diameters (includes bulged and contact) were carried out simultaneously at every step of deformation, the density measurements were carried out using Archimedean principle [17]. Data thus obtained have been used to calculate various parameters so as to establish the exact behaviour of applied stresses with respect to the height strain and densification.

3.0 RESULTS AND DISCUSSION

3.1 Stresses and Height Strain

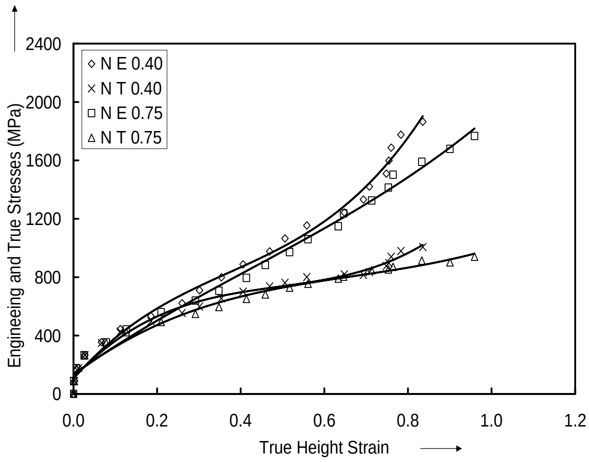

Fig.1: Stresses as a function of strain; N – Nil Lubricant; T – True Stress; E – Engineering Stress

Figure 1 has been drawn between the engineering and true stresses with the true height strains. This figure indicates the influence of initial aspect ratios (preform geometries) under nil lubricating conditions. It is very clearly observed that the characteristic nature of each of the curves is similar. Another critical point can be noticed that the curves corresponding to engineering stress with true height strains are always positioned above in compare with curves corresponding to true stresses with the true height strains. Further observation of Fig. 1 exhibits three different stages of stress rise against strain. The first stage, curves show a decreasing slope indicating the phenomena that the materials start offering resistance to deformation which means the applied load is about to disturb the location of particles which includes pores as well in the preforms. The second stage shown the constant slope, but less steep than the first stage that reveals the phenomena that applied load were much enough to collapse the pore bed and the material start closing down, which ultimately induce enhancement of densification rate. The third stage, shown an increase in applied stress due to an enhancement in area of cross section which stands to bear the load. This leads to drop in true stress values, where as engineering stress values has shown a steep rise which is an index of evidence to exhibit the work hardening in the material both by matrix and geometric as well. The matrix hardening refers to the usual hardening that happens because of the strain induced between the particles, which obstacles the dislocation of the particles, which normally encounter in the conventionally densed material, however the geometric hardening is the special case that happens only with the P/M material as the densification is also continuously rises, in otherwards pores closes during the deformation of material as the consequence the overall geometry deformation of the P/M material is less compare to the identical conventionally produced material thus it promotes further hardening in the P/M material [18]. In regards with the influence of preform geometry the lower aspect ratio (0.40) preforms shown an enhanced level of stress rate. It is due to the fact that the presence of pore bed height is small and so the load being transferred is uniform which leads into improved densification rate. The earlier and faster densification (refer Fig. 2) promotes the material to get harden at little faster as consequence stress is also high, whereas, the larger aspect ratio possesses high volume of pores and pore beds so it gives a room for delayed densification at any given induced strain.

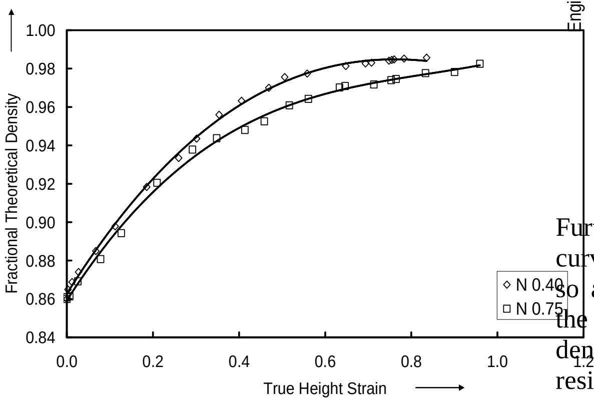

Fig. 2: Density with height strain

3.2 Stresses and Densification

In general, stress can be defined as the internal resistance offered by the material on a particular area of cross section where the load being applied or transferred. This property is based on the density attained by the P/M preforms in effect of induced strain. The density of the preform and the mode in which density attained by the preform are the critical parameters which finalise the mechanical strength of the material has been proved and reported elsewhere [2, 7]. Thus, the values of stresses were taken in ordinate and the percentage of fractional theoretical density attained were taken in abscissa as shown in Fig. 3, to establish the state of behaviour between above said parameters during cold deformation under the influence of preform geometries. Irrespective of the aspect ratio, the characteristic nature is exhibiting similar behaviour for both engineering and true stress against percentage density attained. It has also been found that the stress rate for both the aspect ratio was typically same except at the final stage where 0.40 aspect ratio shown enhanced stress rate with very marginal densification. This is the index of conformity that the strain hardening rate as well as the densification rate attained by the smaller aspect ratio was relatively higher than 0.75 aspect ratio under cold deformation.

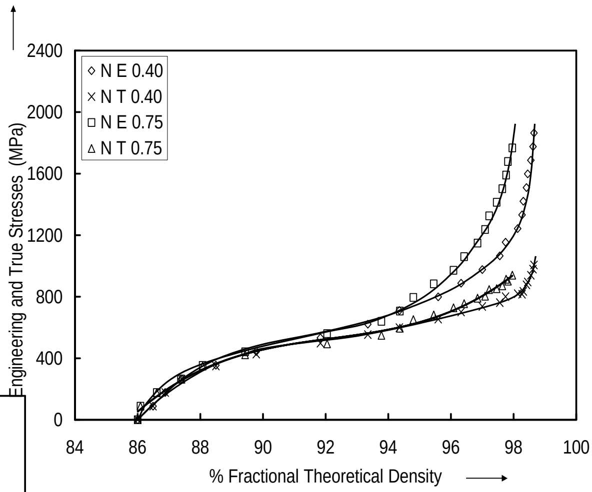

Fig. 3: Stresses as a function of density

Further, it is very clearly observed that these curves are also following three different stages, so analysis of these curves has revealed that in the initial stages, the stress rate with respect to density attained keeps increasing due to the resistance induced by the deforming porous preform. The second stage conforms to a constant slope indicating the steady deformation of porous preform leading to the collapsibility of pores and this indicating higher rate of densification. Finally, the stresses keep increasing quite heavily at a marginal gain in density. This is a region where the work hardening becomes extremely pronounced and the materials start hardening, as a consequence almost all the pores would get desnsify in the central region of deforming preform and residue will try to come out, that is diametrically out wards, as the those region is free deforming region [10] This phenomenon ultimately tends to lead to the initiation and propagation of cracks on the free surfaces of deforming preforms. Therefore, this is the situation should be identified in order to suggest the enforcement of circumferential constraints to reweld the cracks already propagated on the free surfaces of the deforming preforms through the repressive mode of deformation.

3.3 Flow Curve in Log – Log Scale

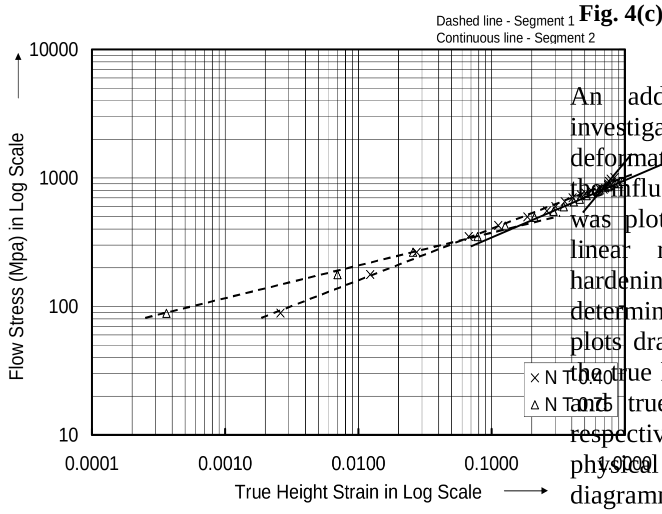

Fig. 4(a): Flow stress against height strain in log – log scale

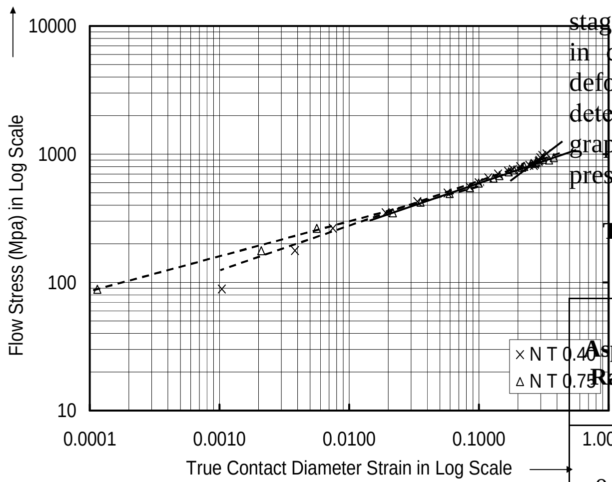

Fig. 4(b): Flow stress against contact diameter strain in log – log scale

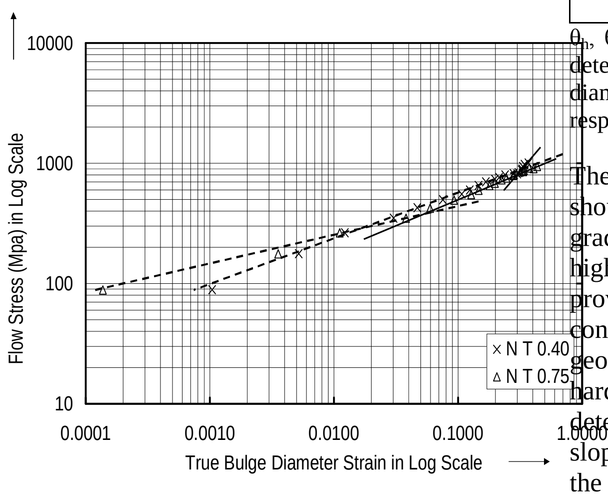

Fig. 4(c): Flow stress against bulge diameter strain in log – log scale

An additional attempt has been made to investigate the strain hardening effect during cold deformation under nil lubricating condition with the influence of aspect ratios. So, the flow curve was plotted in log – log scale to establish the linear relationships, by the process strain hardening co-efficient (i.e., slope) can be easily determined. Figure 4(a), 4(b) and 4(c) are the plots drawn between flow stress in log scale to the true height strain, true contact diameter strain and true bulge diameter strain in log scale respectively for two different aspect ratios. The physical dimensions were described diagrammatically elsewhere [14]. Uniquely, all the curves exhibits two different mechanisms categorized into segment 1 and segment 2 respectively. Segment 1 has been presented as dashed line can be technically named as initial stage of deformation. Segment 2 has been shown in continuous line exhibits the final stage of deformation. The slope of each curve has been determined by measuring the angle ‘θ’ through graphically with horizontal axis which are presented in Table 2.

Table 2: Strain hardening co-efficient of flow curves

Aspect Ratio	Segments	Slope (θ) in Degrees		
		θ_h	θ_{cd}	θ_{bd}
0.40	1	19.1	16.6	18.3
	2	47.1	33.8	46.0
0.75	1	12.9	13.5	11.8
	2	21.0	16.8	20.5

θ_h, θ_{cd}, & θ_{bd} are the slopes or angle of flow curves determined with true height strain, true contact diameter strain and true bulge diameter strain respectively.

The critical observation of Fig. 4(a), 4(b) and 4(c) shows an increasing trend of stress rate exhibiting gradual increase during first segment followed by high enhancement in slope at segment 2. This proves that strain hardening takes place continuously in material due to matrix and geometric deformation as well however, hardening at each step of deformation cannot be determined with this figure. The steep rise of slope at later stage (segment 2) of deformation is the fool proof that hardening effect is high irrespective of the aspect ratio used but, the effect was low in case of higher aspect ratio (0.75). The same phenomena was also been observed in Fig. 1 and 3. An important point can be noticed from Table 2 is that the slope value obtained for true height strain as well as the true bulge diameter strain are almost in par with one another which exhibits the fact that the work hardening takes place in both the linear and lateral direction of the deforming preforms. This effect is substantial at segment 2. Conversely, it can be proved that densification takes place in both axial as well as in lateral direction due to the induced strain. This conforms to the findings of other investigator [19]. But, at segment 2, the extended deformation results in propagation of pores as crack at free surfaces of the deforming preforms. Thus it can be concluded that sintered preforms can be successfully cold deformed with high strength induced due to the geometrical and matrix work hardening and with introduction of repressive mode of deformation to arrest the crack appearance at free surfaces of deforming preforms would yield metallurgically sound product.

4.0 CONCLUSION

The resistance to deformation found to be increasing trend irrespective of aspect ratios against both induced strain and attained densification. However, if follows three different mechanism each exhibit different phenomena that follows; initially stress rise is very high as the applied deformation is about to induce the dislocation of the particles, followed by low stress rise as the dislocation is highly promoted resulted in low stress but high density and finally work hardening phenomena induce again stress values to enhance.

Strain hardening co-efficient have been found in respect of angle for each curve from the horizontal axis graphically by plotting flow curve in a log – log scale. This proves the enhancement of strain hardening through out the deformation however, at later stage of deformation this effect is substantial. Further it has been established that lower aspect ratio (0.40) shows enhanced strain hardening at later stage of deformation where as at initial stage strain hardening effect is almost inline with the higher aspect ratio (0.75).

REFERENCES

[1] F. A. Badia, F. W. Heck and J. H. Tundermann, "Effect of Compositional and Processing Variations On The Properties of Hot Formed Mixed Elemental Powders P/M Steels," Journal of the Iron and Steel Institute, 1951, pp. 255-284.

[2] G. W. Gull, "Mechanical and Metallurgical Properties of Powder Forgings," Powder Metallurgy, Vol.13 No.26, 1970, pp. 156-164.

[3] P.K. Jones, "The Technical and Economic Advantages of Powder Forged Products," Powder Metallurgy, Vol.13 No.26, 1970, pp. 114-129.

[4] S. M. Kaufman and S. Mocarski, "The Effect of Small Amounts of Residual Porosity On The Mechanical Properties of P/M Forgings", International Journal of Powder Metallurgy, Vol.7 No.3, 1971, pp. 19-30.

[5] H. A. Kuhn and C. L. Downey, "How Flow Fracture Affect Design of Preforms for Powder Forging," International Journal of Powder Metallurgy and Powder Technology, Vol.10, 1974, pp. 59-66.

[6] H. N. Tewari and R. Saran, "Analysis of Iron Powder Preform Forging," Transaction of Powder Metallurgy Association of India, Vol. 12, 1985, pp. 83-86.

[7] S. Ramkumar, R. Narayanasamy, K. S. Pandey and K. Mathrubootham, "Effect of Residual Porosity of Mechanical Properties of Cold Deformed Aluminium and Aluminium-4% Copper Powder Preforms," Transaction of Powder Metallurgy Association of India, Vol.15, 1988, pp.3-8.

[8] K.S. Pandey, P. S. Misra and M. L. Mehta, "Hot Extrusion Forging of Iron and Graphite Alloy Powder Preforms Through A Partially Open Hemi-Spherical Die", Quarterly International Journal of Powder Metallurgy Science and Technology, Vol.2 No.1, 1990, pp. 25-35.

[9] K.S. Pandey, "Hot forging of sintered iron and iron-0.35% carbon steel preforms through a partial open hemi-spherical die," Quarterly International Journal of Powder Metallurgy Science and Technology, Vol.5 No.1, 1993, pp.23-32.

[10] H. A. Kuhn, "Deformation Processing of Sintered Powder Materials", Ed. By H.A.Kuhn and A. Lawley, Academic Press, New York, 1978, pp. 99-119.

[11] H. F. Fischmeister, B. Aren and K. E. Eastering, "Deformation and Densification of

Porous Preforms in Hot Forging," Powder Metallurgy, Vol.14 No.4, 1971, pp. 144-163.

[12] K. S. Pandey, "Die designs for hot forgings of sintered iron powder preforms," Quarterly International Journal of Powder Metallurgy Science and Technology, Vol.4 No.1, 1992, pp. 35-46.

[13] W. G. Ball, F .W. Higher, R. A. Mckotch and H. D. Pfingstler, "Replacing Internal with External Lubricants," Advances in P/M and Particulate Materials, Vol.3, 1994, pp. 71-82.

[14] R. Narayanasamy and K. S. Pandey, "A Study of Barreling of Sintered Iron Preforms during Hot Upset Forging", Journal of Materials Processing Technology, Vol.100, 2000, pp. 87-94.

[15] K. S. Pandey, "Effect of Lubrication and Aspect Ratio on Densification Mechanism during Cold Deformation of Sintered Al-4.5%Cu Preforms", Paper was presented in the 1996 World Congress on Powder Metallurgy and Particulate Materials AT Washington DC, USA, in Session No.49, 1995.

[16] W. J. Huppmann and G. T. Brown, "The Steel Powder Forging Process-A General Review," Powder Metallurgy, Vol.2, 1978, pp. 105-112.

[17] K. H. Moyer, "Measuring Density of P/M Materials with Improved Precision," International Journal of Powder Metallurgy and Powder Technology, Vol.15, 1979, pp. 33-42.

[18] R. Narayanasamy, V. Anandakrishnan and K.S.Pandey, "Effect of geometric work hardening and matrix work-hardening on workability and densification of aluminium-3.5%alumina composite during cold upsetting," Materials and Design, Vol.29, 2008, pp. 1582-1599.

[19] K. S. Pandey, "Some Investigation on The Cold Deformation Behaviour of Sintered Aluminium – 4% Copper Alloy Powder Preforms," Journal of Powder Metallurgy Science and Technology, Vol.2 No.4, 1991, pp. 35-44.