ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

DENSIFICATION AND MECHANICAL PROPERTIES OF SINTERED POWDER METALLURGY AISI 4340 STEEL PREFORMS

J. Arivudainambi[1], G. Ranganath[2] and R. Mariappan[3]
[1] Anna University of Technology, Coimbatore, Tamil Nadu, India
[2]Adhiyamaan College of Engineering, Hosur, Tamil Nadu, India
[3]CRD, PRIST University,Thanjavur, Tamil Nadu, India
E-Mail: nambi_ja@rediffmail.com

ABSTRACT

Powder Metallurgy (P/M) manufacturing route has wide industrial applications due to a host of techno-economic advantages. The present investigation has been undertaken to develop and study the characteristics of hot forged AISI 4340 High Strength Low Alloy Steels by using elemental powders through powder metallurgical techniques. The four different aspect ratios namely 0.25, 0.50, 0.75 and 0.90 were prepared by using 1 MN Capacity hydraulic Universal Testing Machine. The green compacts have been sintered at 1100±10°C in hydrogen atmosphere and immediately forged at 1050±10°C by Friction Screw Press. Some of the forged steels were homogenized at 1050±10°C for 1hr, 2hrs and 3hrs in an electrical muffle furnace. The forged and homogenized AISI 4340 steels were subjected in to densification studies and mechanical properties evaluation. Lower aspect ratio preforms such as 0.25 and 0.50 exhibited better densification properties. Two hours homogenized forged steels exhibits better mechanical properties.

Keywords: AISI 4340 steel, powder metallurgy, densification studies, hot forging, mechanical properties, poisson's ratio.

1. INTRODUCTION

Processing of materials through conventional powder metallurgy starts with the consolidation of metal or alloy powders by applying uniaxial or biaxial pressure followed by sintering. The density levels obtained in sintering are always much less than the theoretical values because of the difficulties involved in elimination of small rounded pores. Presence of such micro pores always renders the material weak because these pores act as sites of origination of cracks during service. Elimination of porosity in the sintered components leads for subsequent deformation processing of the preforms such as forging, extrusion, etc. Forging is accepted as economical and an effective method of improving the density as well as the mechanical properties through promotion of homogeneous structure. Powder Preform Forging (PPF) has further advantages viz. optimum utilization of material, single blow finishing operation, and isotropic properties [1-3]. The process of PPF involves subjecting the sintered porous preforms to either hot forging process or cold forging operations such as upsetting or repressing in closed dies. Using elemental powders of metals or pre alloyed powders as the raw materials for the PPF process. The final component in the forged conditions can attain properties superior to wrought materials. The quality of the product obtained through PPF is very much influenced by the various process parameters such as forging temperature, initial preform density and alloying elements [4]. Some of the limitations of hot forging are oxidation and decarburization of the surface of billets, excessive die wear, poor surface finishing, and the induction of thermal stresses as a result of cold forging has been gaining importance in recent times [4]. The demand for cheaper but high strength structural alloys has driven the P/M industry to seek newer compositions with wider applications of Fe-C alloys. Such alloys find applications for automobile, aerospace, and power tools [5]. In the present investigation High Strength Low Alloy steel such as AISI 4340 has been prepared form the elemental powder and subsequently sintered in hydrogen atmosphere. Sintered steels have been immediately forged and homogenized at 1050±10°C for one hour, two hours and three hours. Forging characteristics such densification mechanism and mechanical properties of AISI 4340 have been studied.

2. EXPERIMENTAL DETAILS

Atomized iron powder, chromium, manganese and nickel powders were supplied by Hoganes India Ltd., Pune, India. The chemical composition of the AISI 4340 powder is as shown in the Table-1. The basic characteristics of powder blend (AISI 4340) such as flow, apparent density, compressibility, and sieve analysis have been carried out using standard rate methods

Table-1. Chemical composition of AISI4340 steel.

% C	% Mn	% Cr	% Si	% Ni	% Mo	% Fe
0.4 %	0.75 %	0.8 %	0.3 %	1.9 %	0.25 %	Balance

of testing. The characteristics of the powder blends are tabulated in Table-2. The Powder morphology of the powder blend is shown in the Figure-1. The blended powder mass was then compacted into cylindrical billets of aspect ratios (Height/Diameter) such as 0.25, 0.5, 0.75 and 0.90 were prepared by Universal Testing Machine of

ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

100 tonnes capacity. The pressure level of 450±10MPa was applied during compaction. Zinc Lubricant was used to avoid the various frictions between the die, punch and powder particles. After compaction indigenously developed ceramic coating was applied on the compacts and dried for 24 hrs. Sintering was carried out in a tubular furnace with protective atmosphere such as hydrogen at a temperature of 1100 ± 10^{0}C for a period of 120 minutes.

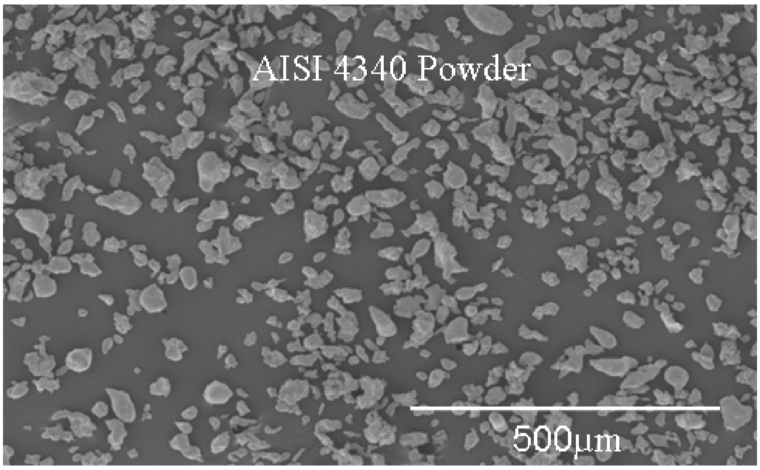

Figure-1. Powder morphology of AISI 4340 steel powder.

The flow rate of the reducing gas is 250 ml per minute. Hot upsetting of the sintered preforms followed immediately after the sintering process. Dimensional measurements were accurately carried out after each step of hot deformation. Similarly density measurements were made after each deformation step by applying Archimedes's principle. The axial upsetting was continued up to the instance of formation of fine surface cracks. The forged AISI 4340 steel subjected in to mechanical properties evaluation. The fractographs of the tensile samples are also analyzed.

Table-2. Sieve size analysis of AISI 4340 powder.

S. No	**Sieve size** (μm)									
	+150	+120	+106	+ 90	+75	+63	+53	+45	+38	-38
Wt retained (%)	5.42	13.42	4.06	1.20	24.19	11.49	14.22	6.37	1.70	17.54
Cum. wt retained (%)	5.42	18.84	22.9	24.10	48.29	59.78	74.00	80.37	82.70	99.61
Apparent density (g/cc)	2.84									
Flow rate (S/ 100g)	27.5									

3. RESULTS AND DISCUSSIONS

3.1 Compressibility behaviour of HSLA powders

Figure-2 has been drawn to exhibit and asses the load required to attend the particular level of density which can be fixed as initial perform density of the preforms. Compressibility plots are expressed between percent theoretical density achieved and the applied pressure.

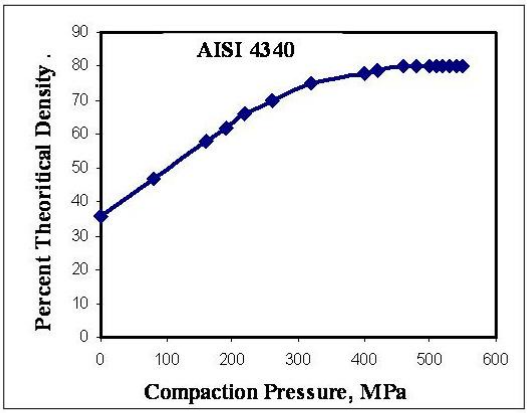

Figure-2. Compressibilty behaviors of different AISI 4340 steel powders.

Based on these curve a pressure equivalent to 450±10MPa was required in order to obtain a density level in the same range of 80±1 percent of theoretical. More over the presence of chromium oxide on the surface of the particle resist during the time of compaction. This pressure range was adequate to consolidate the AISI 4340 elemental powder blend. Hence, it was decided to carry out compaction at 460MPa pressure. Also, ejection of the compacts from the die was so smooth that no damage to any dimension has been observed. During compaction a little amount of spring back in the green compacts has been observed to the tune of 0.3%. This may be due to release of elastic strains in the AISI 4340 powders.

3.2 Sintering behaviour of AISI 4340 steel preforms

Sintering is a very important step in powder metallurgy as major structural changes occur in compacted powders. A silica tubular furnace with programmable temperature controller with ±1°C accuracy has been employed for this present study. Sintering temperature, time and atmosphere influences the densification behaviour and hence the properties of the sintered product. In the present study, sintering temperature and time have been optimized at 1150°C and 2 hrs. The influence of chemical composition on densification and mechanical properties are discussed below.

3.2.1 Influence of chemical composition on densification parameter

Sintering of green AISI 4340 steel compacts was carried out in hydrogen atmosphere at 1150°C for 2 hrs. The details have been given elsewhere. Measured (green and sinter densities) and calculated (theoretical and densification parameter) values of HSLA steels are given in the Table-3. Densification Parameter has been calculated by using the formula given below.

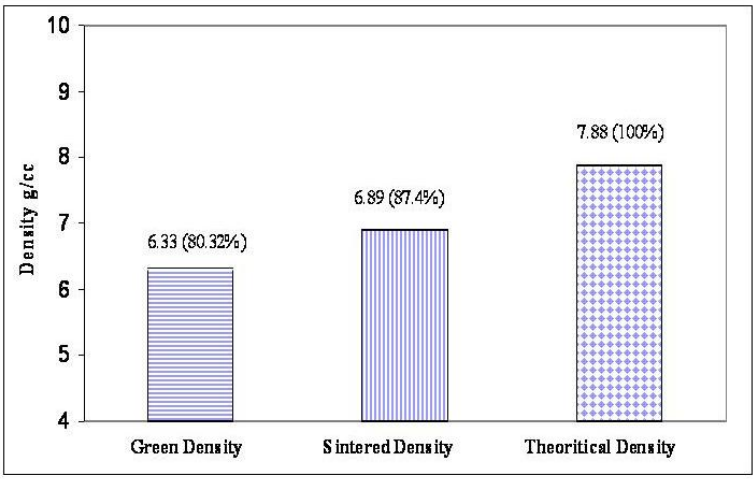

Figure-3. Densities of AISI 4340 steel sintered in hydrogen atmosphere.

The Densification Parameter of 0.3391 is exhibited for the standard AISI 4340 steel powders. Figure-3 shows the density bar graph for the AISI 4340 steels.

ΔD = (sintered density - green density) / (theoretical density - green density)

Table-3. Densities of sintered AISI 4340 steel performs.

Composition	Compaction pressure 450±10MPa			
	Green density (g/cc)	Sintered density, (g/cc)	Theoretical density, (g/cc)	Densification parameter
AISI 4340	6.326	6.8880	7.877	0.3391

3.3 Hot forging characteristics

3.3.1 Densification characteristics of AISI 4340 steel preforms

Figure-4 is drawn between the influence of initial perform geometry on the densification modes of sintered AISI 4340 steel preforms (made of elemental powder blend) during hot forging at 1050±10°C. A clear visual observation was made from the Figure-4 and it indicates that lower aspect ratio (Ho/Do) preforms such as 0.25 and 0.5 have been more densified than 0.75 and 0.90 aspect ratio preforms. The reason for higher densification in lower aspect ratio preforms is quick transfer of load due to reduced damping phenomena. The densification pattern in two larger aspect ratio preforms namely 0.75 and 0.90 was found to be almost on the identical mode but only with the mild marginal difference.

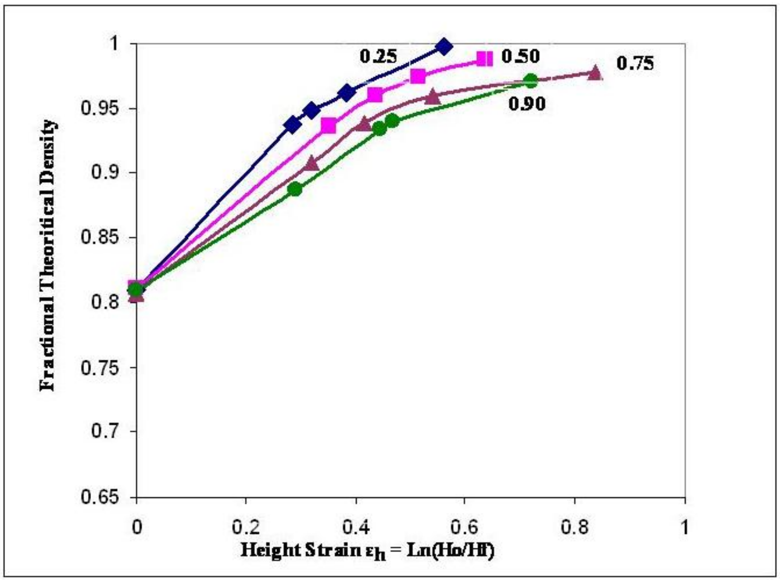

Figure-4. Height strain Vs fractional theoritical density for the AISI 4340 steel preforms.

Table-4. Co-efficient of polynomial equation of the form.

Aspect ratio	Co-efficient	AISI4340 P/M steel
O.25	Ao	0.8106
	A_1	0.4876
	A_2	-0.3036
	$\lvert A_1/A_2\rvert$	1.6061
O.50	Ao	0.7953
	A_1	0.3202
	A_2	-0.0525
	$\lvert A_1/A_2\rvert$	6.0990
O.75	Ao	0.7952
	A_1	0.4010
	A_2	-0.2323
	$\lvert A_1/A_2\rvert$	1.7262
O.90	Ao	0.7998
	A_1	0.4492
	A_2	-0.2879
	$\lvert A_1/A_2\rvert$	1.5602

Further the densification curves were found to follow a second order polynomial between the attained fractional density and the true corresponding height strains. The relation expressed is as under the equation 1.

$(\rho f/\ \rho th) = Ao + A_1 \ln (Ho/Hf) + A_2 \ln (Ho/Hf)^2$ … (1)

Where (ρf/ ρth) = Fractional Theoretical Density,

In (Ho/Hf) = True Height Strain and

A_1, A_2 and A_3 are empirically determined constants.

The empirically determined constants are tabulated in Table-4. This table indicates that the constant Ao virtually is in close conformity with the initial preform density irrespective of the aspect ratio. Therefore during the hot forging the constant Ao does not contribute to densification in anyway. However the constant A_1 is always found to be positive and is multiplied by the height strain implying there by that this constant in fact facilitates densification. But, always the negative values of constant A_2 with a low magnitude simply taper off the densification and thus, is determined [5].

3.3.2 Poisson's ratio

Poisson's ratio is one of the most fundamental and practical dimensionless quantity which is extensively used in the forming of suitable P/M parts. The production of P/M parts through hot upsetting involves substantial flow of material before repressing action is employed. However, the repressing action must be introduced at the stages where surface cracking just begins. Therefore, it is apparent that the production of P/M parts in the near vicinity of theoretical density, the design of preform geometry and forming dies are dependent upon Poisson's ratio [5]. This can be defined as the ratio between the diameter strain and height strain; it is proved [6] that the Poisson's ratio for plastic deformation of fully dense material is 0.5. During hot upsetting of sintered powder metal, some material flows into pores and there is decrease in volume. For a given height reduction, the diameter of a powder metal cylinder will expand lesser than a fully densed material. Therefore, the Poisson's ratio for plastic deformation of sintered powder material will be less than one-half and will be a function of the pore volume fraction. Experimentally, Poisson's ratio can be determined by measuring the instantaneous deformed diameter and height for each step of deformation, the resulting strain calculated for diameter and height was plotted in Figure-5 and the ratio of these two parameter for the corresponding curve gives the value of Poisson's ratio. Further, it can be noted that the 45 degree line representing the relationship between diameter strain and height strain for a fully dense material and the curves for porous material are below the dashed line but gradually become parallel to it as full density is approached [9]. Figure-5 has been drawn between true diameter strain and true height strain to demonstrate the variation in the values of poisson's ratio. The curves corresponding to lower aspect ratios such as 0.25 and 0.50 are much nearer to the theoretical line where as the data points 0.75 and 0.90 are slightly far away from theoretical 45 degree line. More over these curves for 0.75 and 0.90 are lying below the curves corresponding to data points of preforms of 0.25 and 0.50 initial aspect ratio. It is observed that all data points remain below the theoretical line irrespective of aspect ratio ascertaining the fact that the values of poison's ratio remain that less than 0.5.

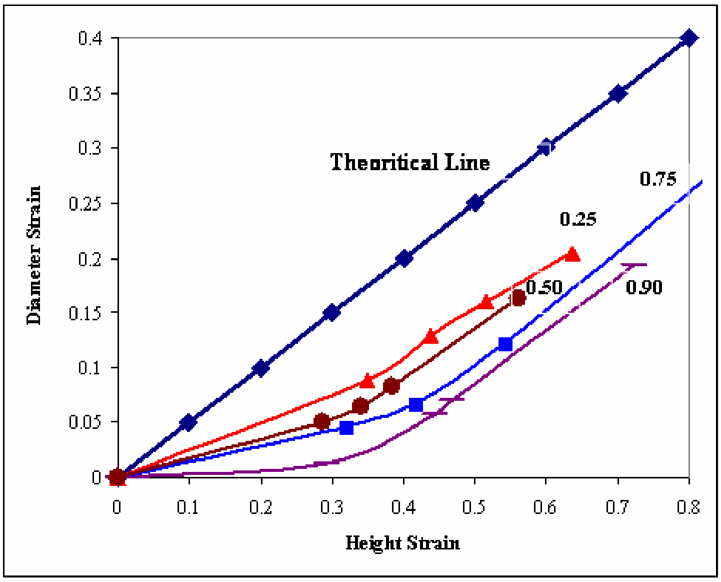

Figure-5. Diameter strain Vs height strain for the sintered AISI 4340 steel performs.

Figure-6 has been drawn to demonstrate the influence of initial aspect ratio and the relationship between poisson ratio (υ) and the percentage of theoretical density % (ρf/ ρth). From Figure-6 it is observed that the influence of initial aspect ratio is marginal [8], however characteristically the curves shown are similar. When the attained density is almost 100 percent, these curves indicate the tendency to approach to a limiting value of poisson's ratio equal to 0.5.

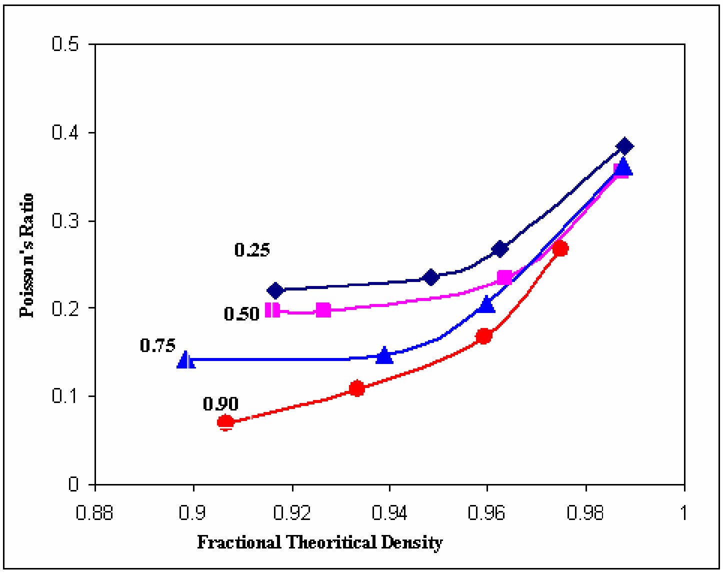

Figure-6. Poisson's ratio Vs fractional theoritical density for the sintered AISI 4340 steel.

VOL. 6, NO. 5, MAY 2011 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

3.3.3 Mechanical properties of hot forged AISI 4340 powder performs

The mechanical properties of forged and homogenized AISI 4340 steels are tabulated in the Table-5. From the Table-5 forged AISI 4340 steel is having the tensile strength of 724MPa with the elongation of 7 percent. But the homogenized steels are having higher tensile strengths of 746MPa, 764MPa and 762MPa for homogenization of one hour, two hours and three hours, respectively. Similarly after homogenization the hardness and elongation values are also increased. Especially the steels homogenized for two hours shows better tensile strength and hardness. But for three hours homogenized 4340 steels do not show more improvement in tensile strength and hardness [7]. The stress - strain curves for forged and homogenized p/m steels are shown in the Figure-7.

Table-5. Mechanical properties of hot forged and homogenized AISI 4340 powder performs.

Condition	**Yield strength MPa**	**Young's modulus GPa**	**Tensile strength MPa**	**Percent elongation** (%)	**Hardness HRC**
As forged	496	176	724	6.9	30
1 hr Homogenization	514	186	746	9.6	34
2 hr Homogenization	538	186	764	11.6	36
3hr Homogenization	534	180	762	10.8	36

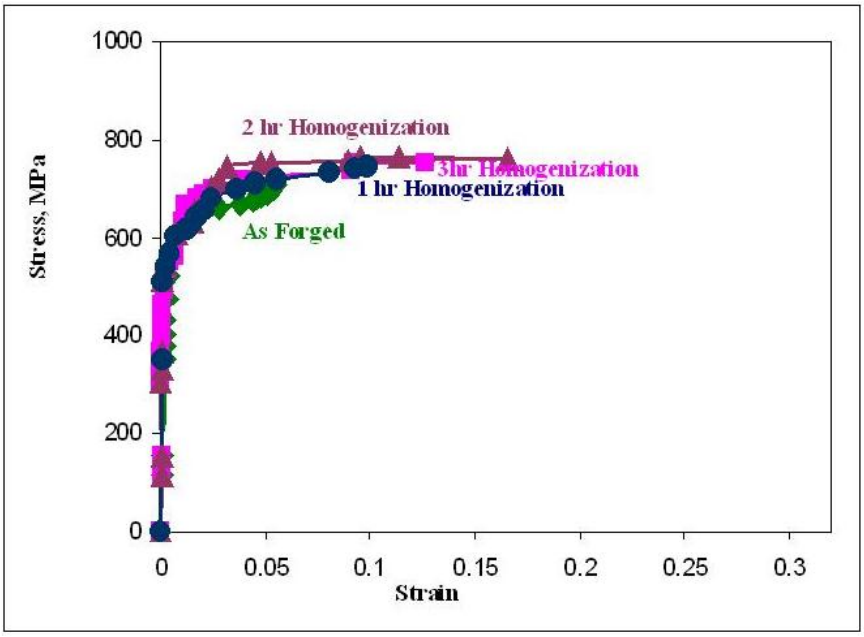

Figure-7. Stress - strain curves for forged and homogenized P/M steels.

The fracture surface of the forged and homogenized P/M 4340 steels were examined in a Scanning Electron Microscope, which is shown in the Figure-8. SEM fractograph show the combination of cleavage and quasi cleavage for the forged steels, which causes poor elongation. But for one hour homogenized steels are having the combination of smaller dimples with some quasi cleavage. From the Figure-8, the two hour homogenized and 3 hours homogenized show the bigger dimples which leads to completely ductile modes of failure, as it is evident form its elongation.

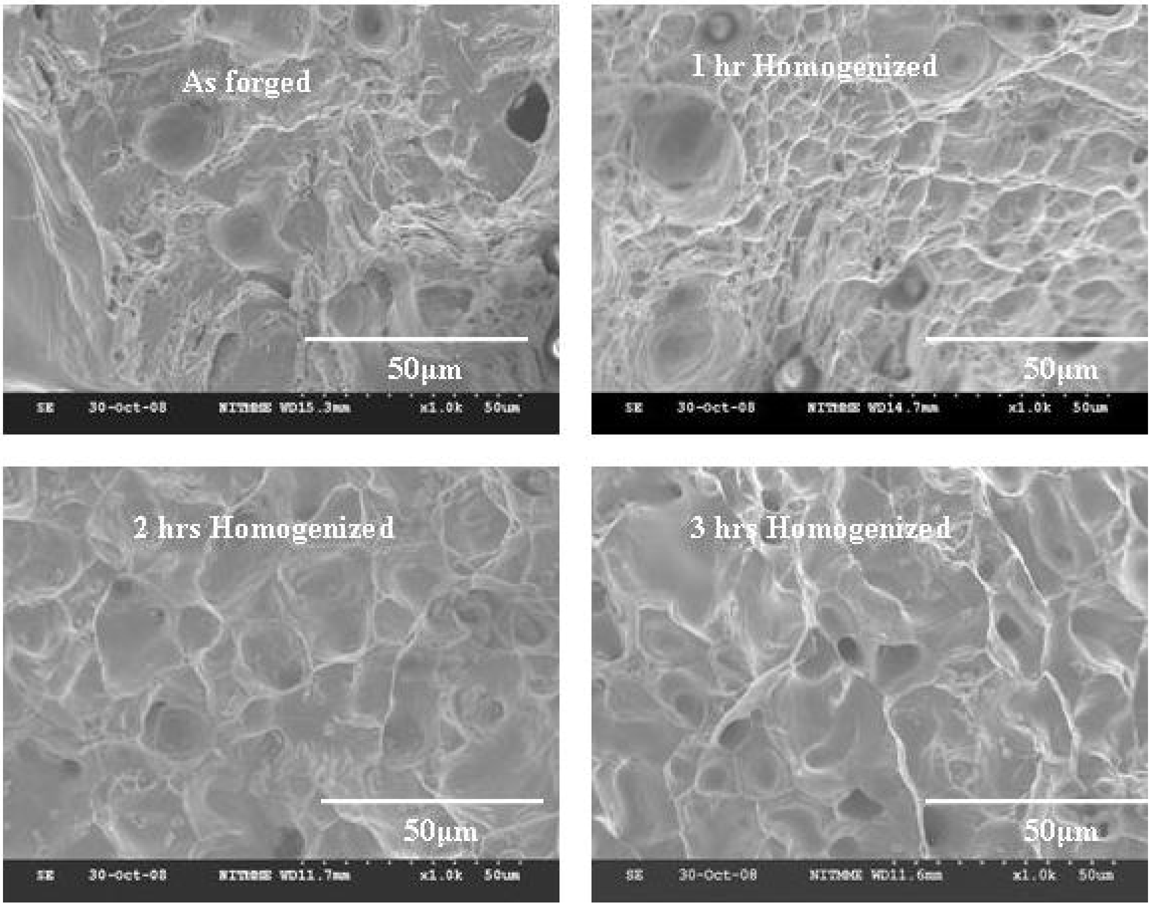

Figure-8. SEM - fractographs of forged and homogenized P/M 4340 steels.

4. CONCLUSIONS

Based on the analysis of the experimental data and the calculated parameter, the following major conclusions are drawn:

a) Irrespective of the composition, the characteristic nature of the compressibility plots between % $(\rho f/\rho_{th})$ and pressure applied in MPa is similar and provides the information to select an appropriate load for compaction purposes with the minimum tool wear.
b) Characteristic nature of densification curves between % attained theoretical density and the true height strain curves are found to correspond to a second order polynomial of the form (pf/pth) =a0+a1 ln (H0/Hf)+a2 $[\ln (H0/Hf)]^2$ where a0,a1 and a2 are empirically determined constants dependent upon the initial aspect ratio.
c) Poisson's ratio with respect to density attained has been found to be mildly dependent upon the initial perform aspect ratio. Further, the basic nature has been found to be same when the relationship is established between the Poisson's ratio (υ) and the % theoretical density attained. These curves have tended to approach to a limiting value of 0.5 in the near vicinity of 100% densification.
d) Data points for the relationship between the true diameter and the true height strains lie upsetting conditions, cent percent densification is not possible.
e) The mechanical properties such as tensile strength and elongations are improved after optimum time of homogenization (two hours), which is evident from the fractographs.

REFERENCES

[1] German R. M. 1998. Powder Metallurgy of Iron and Steel. John Wiley and Sons, Inc., New York. pp. 276-279.

[2] Kuhn H.A., Downey C. L. 1971. Deformation characteristics and plasticity theory of sintered materials. International Journal of Powder Metallurgy. 2(1): 15-25.

[3] Lee S. R., Lee Y. K., Park C. H., Yang D. Y. 2002. A new method of preform design in hot forging by using electric field theory. International Journal of Mechanical Science. 44(4): 773-792.

[4] R.Chandramouli, T. K. Kandavel, D. Shanmugasundaram, T. Ashok Kumar. 2007. Deformation, densification, and corrosion studies of

ARPN Journal of Engineering and Applied Sciences

sintered powder metallurgy plain carbon steel perform. Materials and Design. 28: 2260-2264.

[5] Pandey K. S. 1991. Some investigations on the cold deformation behavior of sintered Aluminum - 4% copper alloy powder preforms. Quarterly International Journal of Powder Metallurgy Science Technology. 2(4): 45-54.

[6] Sowerby R., O'Reilly I., Chandrasekaran N., Dung N.L. 1984. Materials testing for cold forging. Journal Engineering Materials Technology. 106: 101-106.

[7] W B James, M J McDermott and R A Powell. 1988. Powder Forging. Metals Handbook. Vol. 14, 10th Edition.

[8] Pandey K. S. 1989. Salient Characteristics of High Temperature Forging of Ferrous Performs Key Engineering Materials. Vols. 29-31. Trans Tech Publications. Switzerland. pp. 465-86.

[9] A. Rajesh Kannana, K.S. Pandey, S. Shanmugam. 2008. Some investigation on the cold deformation behaviour of sintered iron-0.8% carbon alloy powder performs. Journal of Materials Processing Technology. 203: 542-547.