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EXPERIMENTAL APPROACH ON DENSIFICATION AND MECHANICAL PROPERTIES OF SINTERED POWDER METALLURGY AISI 4140 STEEL PREFORMS

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ABSTRACT

Due to the large number of techno-economic advantages, the powder metallurgy (P/M) manufacturing route has wide industrial applications. The investigation has been undertaken to develop and study the characteristics of hot forged AISI 4140 High Strength Low Alloy Steels by using elemental powders through powder metallurgical techniques. 1 MN Capacity hydraulic Universal Testing Machine has been used to prepare the four different aspect ratios namely 0.25, 0.50, 0.75 and 0.90. In the presence of hydrogen atmosphere, the green compacts have been sintered at 1100±10°C and it was 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 4140 steels were subjected to densification studies and mechanical properties evaluation. Lower aspect ratio preforms such as 0.25 and 0.50 show better densification properties. The two hour homogenized forged steels exhibit better mechanical properties.

Keywords: AISI 4140 steel, powder metallurgy, densification studies, hot forging, mechanical properties, poisson's ratio.

1. INTRODUCTION

By applying uniaxial or biaxial pressure followed by sintering process the processing of materials through conventional powder metallurgy starts with the consolidation of metal or alloy powders. Here, the density levels obtained in sintering process are always much less than the theoretical values because of the difficulties involved in elimination of small rounded pores. Though the pores act as sites of origination of cracks during service, the presence of such micro pores always renders the material weak. Elimination of porosity in the sintered components leads to the subsequent deformation processing of the preforms such as forging, extrusion, etc. Here the forging is accepted as economical and it is an effective method of improving the density as well as the mechanical properties through promotion of homogeneous structure. The various other advantages in Powder Preform Forging (PPF) are 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. By 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]. Under hot forging process, some of limitations like 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 current investigation, High Strength Low Alloy steel such as AISI 4140 has been prepared from 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. The forging characteristics such as densification mechanism and mechanical properties of AISI 4140 have been studied.

2. EXPERIMENTAL DETAILS

The essential requirements for the experimental purpose, the various powders such as Atomized iron powder, chromium, manganese and nickel powders were supplied by Hoganes India Ltd., Pune, India. In Table-1, the chemical composition of the AISI 4140 powder is shown. The basic characteristics of powder blend (AISI 4140) such as flow, apparent density, compressibility, and sieve analysis have been carried out using standard rate methods of testing.

Table-1. Chemical composition of AISI4140 steel

% C	% Mn	% Cr	% Si	% S	% Mo	% Fe
0.4	0.72	0.78	0.3	0.03	0.25	Balance

In Table-2, the characteristics of the powder blends are tabulated. 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 prepared by Universal Testing Machine of 100 tonnes capacity. The pressure level of 450±10MPa was applied during compaction. The various frictions between the punch, die and powder particles can be avoided by using Zinc Lubricant. After compaction, indigenously developed ceramic coating was applied on the compacts and dried for 24 hours. Sintering was carried out in a tubular furnace with protective atmosphere such as hydrogen at a temperature of 1100 ± 100C for a period of 120 minutes. The flow rate of the reducing gas is 250 ml per minute. Hot upsetting of the sintered performs followed immediately after the sintering process. Dimensional measurements were accurately carried out after each step of hot deformation. Similarly by applying Archimedes's principle, the density measurements were made after each deformation step. The axial upsetting was continued up to the instance of formation of fine surface cracks. The forged AISI 4140 steel was subjected to the mechanical properties evaluation. The fractographs of the tensile samples are also analyzed.

Table-2. Sieve size analysis of AISI 4140 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-1 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.

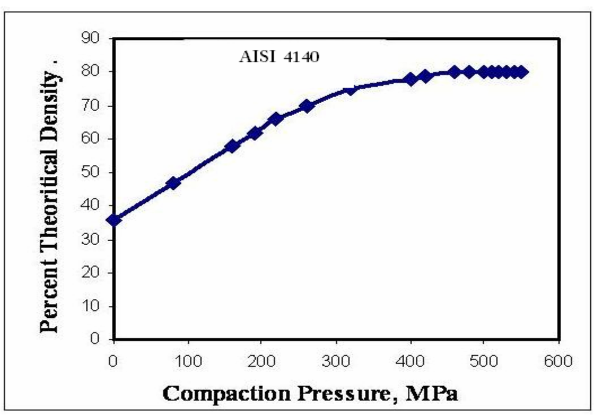

Figure-1. Compressibilty behaviors of different AISI 4140 steel powders

Based on this 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 value. At the time of compaction the resistance of the surface will be improved in the presence of chromium oxide particle on the surface. The pressure range thus obtained is adequate to consolidate the AISI 4140 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 there is 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 4140 powders.

3.2 Sintering behaviour of AISI 4140 steel preforms

As major structural changes occurring in compacted powders sintering is a very important and essential step in powder metallurgy, 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 hours. The influence of chemical composition on densification and mechanical properties are discussed below.

3.2.1 Influence of chemical composition on densification parameter

In the presence of hydrogen atmosphere, the sintering of green AISI 4140 steel compacts was carried out in 1150°C for 2 hrs. The details have been given elsewhere. In Table-3, the measured (green and sinter densities) and calculated (theoretical and densification parameter) values of HSLA steels are tabulated. Densification Parameter has been calculated by using the formula given below.

Table-3. Densities of sintered AISI 4140 steel preforms.

Composition	Compaction pressure 450±10MPa			
	Green density (g/cc)	**Sintered density,** (g/cc)	**Theoretical density,** (g/cc)	**Densification parameter**
AISI 4140	6.326	6.8880	7.877	0.3391

The Densification Parameter of 0.3391 is exhibited for the standard AISI 4140 steel powders. Figure-2 shows the density bar graph for the AISI 4140 steels.

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

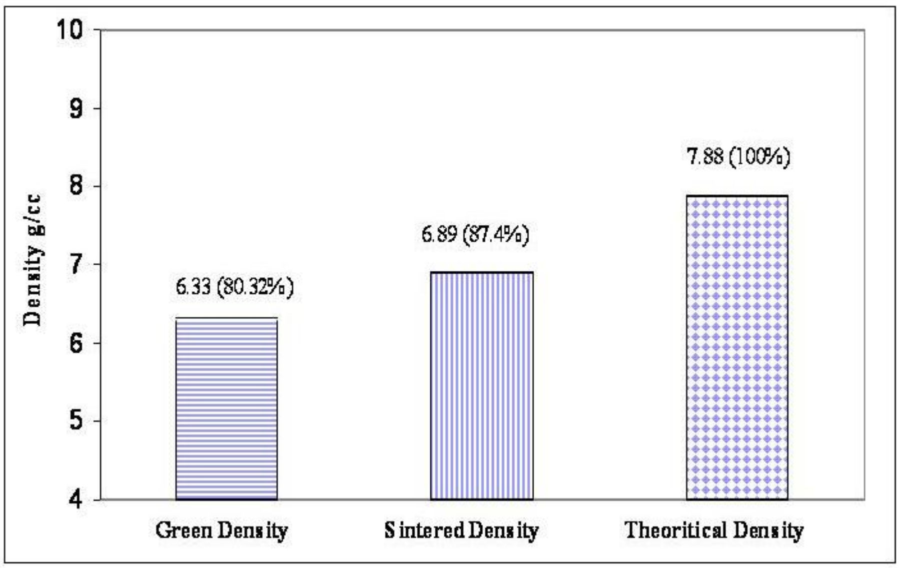

Figure-2. Densities of AISI 4140 steel sintered in hydrogen atmosphere

3.3 Hot forging characteristics

3.3.1 Densification characteristics of AISI 4140 steel preforms

The influence of initial preform geometry on the densification modes of sintered AISI 4140 steel preforms (made of elemental powder blend) during hot forging at 1050±10°C was shown in Figure-3. A clear visual observation was made from the Figure-3 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.

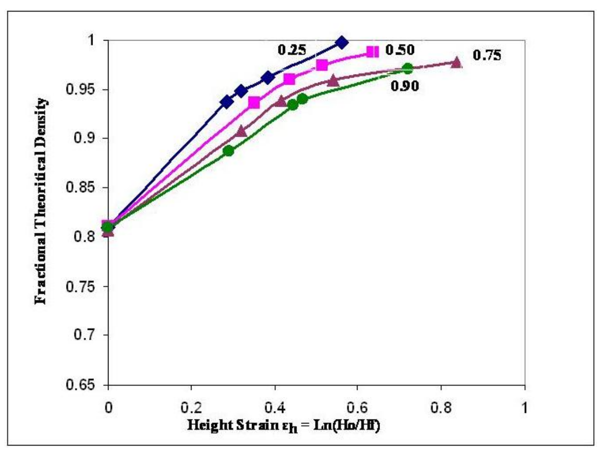

Figure-3. Height strain Vs fractional theoritical density for the AISI 4140 steel preforms

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

Aspect ratio	Co-efficient	AISI4140 P/M steel
O.25	Ao	0.8106
	A_1	0.4876
	A_2	-0.3036
	$\|A_1/A_2\|$	1.6061
O.50	Ao	0.7953
	A_1	0.3202
	A_2	-0.0525
	$\|A_1/A_2\|$	6.0990
O.75	Ao	0.7952
	A_1	0.4010
	A_2	-0.2323
	$\|A_1/A_2\|$	1.7262
O.90	Ao	0.7998
	A_1	0.4492
	A_2	-0.2879
	$\|A_1/A_2\|$	1.5602

In the above graphical representation, 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.

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

Where

$(\rho f/\ \rho th)$ = Fractional Theoretical Density

In (Ho/Hf) = True Height Strain

A_1, A_2 and A_3 are empirically determined constants.

In Table-4, the empirically determined constants are tabulated. 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

The most fundamental and practical dimensionless quantity, called as Poisson's ratio 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-4 and the ratio of these two parameters 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-4 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.

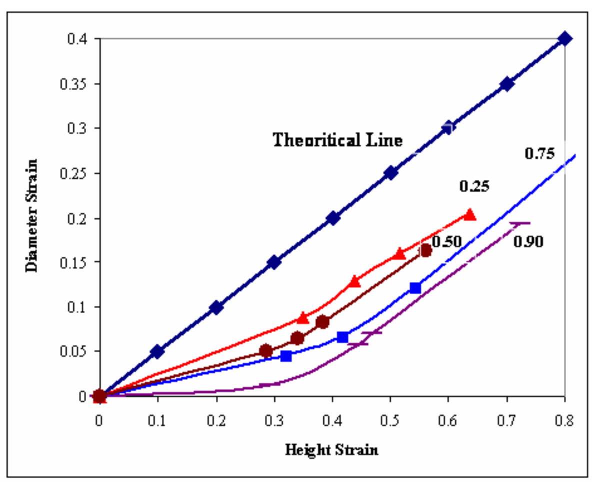

Figure-4. Diameter strain vs. height strain for the sintered AISI 4140 steel preforms.

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Figure-5 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-5 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.

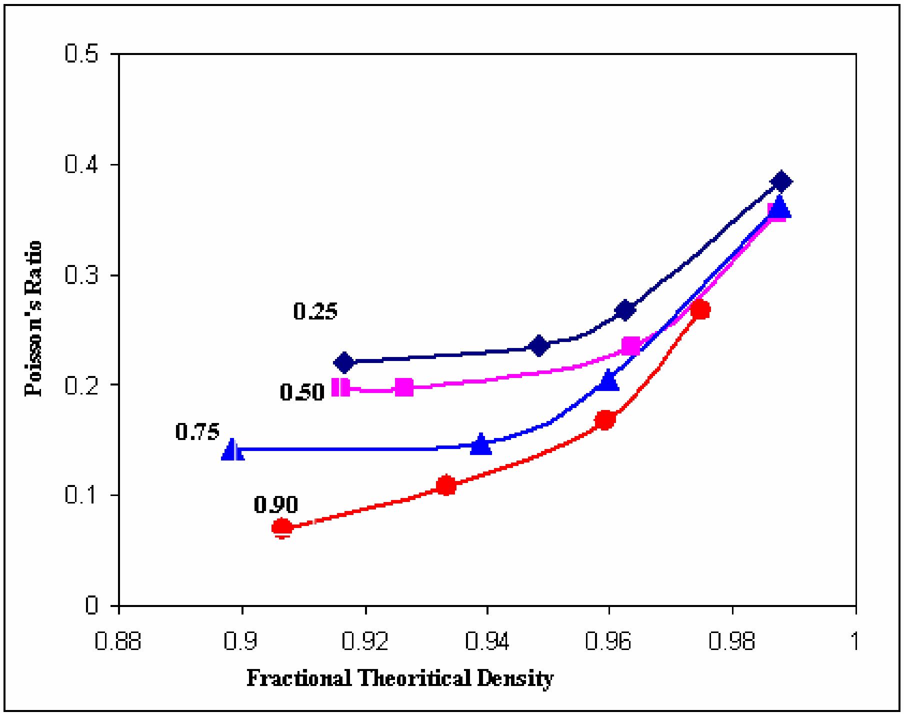

Figure-5. Poisson's ratio Vs fractional theoritical density for the sintered AISI 4140 steel

3.3.3 Mechanical properties of hot forged AISI 4140 powder performs

In Table-5, the mechanical properties of forged and homogenized AISI 4140 steels are tabulated. From the Table-5, forged AISI 4140 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 4140 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-6.

Table-5. Mechanical properties of hot forged and homogenized AISI 4140 powder performs

Condition	Tensile strength MPa	Fracture stress MPa	Percentage of elongation (%)	Percentage of reduction in area (%)	Hardness VPN
As forged	655	417.1	25.7	56.9	197
1 hr Homogenization	670	420	25.7	56.9	200
2 hr Homogenization	672	422	26.2	56.9	200
3hr Homogenization	675	427	26.5	60.0	198

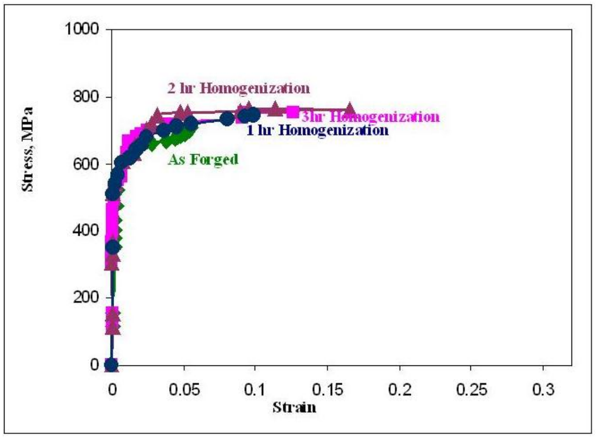

Figure-6. Stress - strain curves for forged and homogenized P/M steels

4. CONCLUSIONS

From the above analysis, the experimental data and the parameter has been calculated, the major conclusions are drawn as follows:

a) 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, under the condition of composition irrespective;
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) 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. And also the Poisson's ratio with respect to density attained has been found to be mildly dependent upon the initial perform aspect ratio. These curves have tended to approach to a limiting value of 0.5 in the vicinity of 100% densification;
d) Cent percent densification is not possible because data points for the relationship between the true diameter and the true height strains lie in upsetting conditions; and
e) It was known that, the mechanical properties such as tensile strength and elongations are improved after optimum time of homogenization (two hours).

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