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Evaluation of Mechanical Properties of Sintered Hot Upset Forged Square Cross Section Bars of Chromium-Molybdenum Low Alloy Steels

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Abstract: *Present investigation pertains to evaluate the tensile properties of sintered hot forged and oil quenched and also homogenized, but furnace cooled specimens which were machined from square cross section bars of approximate dimensions of ~13mm x ~13mm x~100±5mm of Fe-0.16%C, Fe-0.16%C-0.7%Mn, Fe-0.16%C-1.0%Cr-0.55%Mo and Fe-0.16%C-2.25Cr-1.05%Mo P/M steels prepared from elemental powders. Green compacts of homogeneously blended powders of all compositions were prepared with initial aspects ratio of 1.34 with diameter being 27.5mm using suitable compaction die set assembly on 1.0MN capacity UTM to a density level of 0.85±0.01 of theoretical employing controlled pressures in the range of 490±10MPa and taking pre – weighed powder blends. All green compacts were protected during sintering by applying thin film of indigenously developed ceramic coating on the entire surfaces. Ceramic coated compacts were sintered in an electric muffle furnace at 1373±10K for a period of 120 minutes. All sintered preforms of each com position were hot forged on a 1.0MN capacity friction screw press to square cross section bars of afore mentioned dimensions. Once the forging operation was completed 10-12 bars were quenched in linseed oil and nearly 12 bars were homogenized at sintering temperature for one hour and then cooled inside the furnace itself. Standard tensile specimens were machined and tested on Hounsfield Tensometer for evaluating tensile properties which were appreciably close to the properties reported in literature for the above steels. Microstructure of specimens containing chromium and molybdenum exhibited few un-dissolved particles along with the presence of fine pores. SEM Fractography revealed mixed mode failure mostly ductile and partly brittle. These steels also exhibited adequate ductility as is exhibited by conventionally produced steels. Thus, this investigation shows the way how to produce high density P/M steels which can be used in structural applications.*

Key Words: *applications, bars, composition, density, dissolved, ductility, failure, furnace cooled, fractography, hot forged, microstructures, sintered, structural, tensile.*

I. Introduction

Past seventy years have witnessed a tremendous growth in the area of powder perform forging/ extrusion/rolling either cold/warm or hot to produce components to near net shape with almost one hundred per cent density. Further it has been believed over the past several decades that higher is the density, improved are the mechanical properties, but, the last remaining residual porosity becomes very vital to all related properties of the product .However, the reports also indicate that merely attaining the high density is not an index of improved mechanical properties. This very aspect can be referred elsewhere[1-3].The conventional P/M route has been to consolidate the metal or blended powders in a suitable die, punch and bottom insert assembly at enhanced pressures and sintering them under the protective or the reducing atmospheres for a given length of time and same were employed directly in service. However, the demands raised by the automobile, nuclear and space industries were that the parts produced must serve the requirements of structural applications and, hence, one of the deformation processes were thought to be essential to be employed even though an open option of liquid phase sintering or liquid phase infiltration processes were available to enhance sound metallurgical bonds. But, the period beyond seventies saw a sea change in producing forged P/M parts for direct applications with improved efficiency. In majority of the cases, P/M forged parts exhibited higher range of mechanical properties which were isotropic in nature then the conventionally produced ingot metallurgy (I/M) parts.

P/M parts are practically well suited for fast high volume production of countless parts in the automotive, various appliances, agricultural equipment, business machines, electrical and electronic, power tools ordnance and machine tools industries. However, they also find extensive applications in the aerospace, nuclear and other industries [4]. Thus, powder metallurgy offers the engineers and scientists, a means of conserving materials, minimizing machining and by securing a uniform product at reasonable costs [5]. In industries, the forming of structural components from porous materials, either directly from atomized powders or from blended powders, but, sintered preforms is becoming a popular route. This is due to the fact that P/M forming processes result in savings in energy and materials in addition to quality improvement. In automotive industries, the weight reduction results in favourable operating conditions of the engine in terms of reduced exhaust gas emissions and vibrations. Thus, lowering down the fuel consumptions .Connecting rod is the bulk component, i.e., required in automobiles, and, hence, the P/M forming route is in strong competition with the conventional processes such as casting and forgings routes [6].

In powder preform forging or hot isostatic pressing, the density and the mechanical properties of components and parts is raised to values to those of wrought products [7]. Plastic deformation of sintered powder materials are similar to that of conventionally fully dense materials, but, there are additional complications due to the substantial volume fraction of voids in the perform materials. In particular, the voids must be eliminated during deforming operation so that a sound metallurgical structure is obtained [8]. The forging of sintered powder performs has been shown to be a process capable of producing higher density P/M parts for high stress applications where porosity must be minimized or completely eliminated. Mechanical properties of powder forged parts depend upon the processing parameters, the composition, the sintering time and forging operations [9]. Pores present in a P/M parts act as stress raisers and also provide initiation sites for corrosion, especially in an environment containing chloride ions. However, industrial use of stainless P/M products has increased in the recent years due to their improved corrosion properties and at relatively low cost. Porosity in P/M parts makes them highly susceptible to crevice corrosion [10]. However, the probability of fracture is mainly dependent upon the volume fraction of pores and only to a small extent depends on pore size [11]. However, the fatigue properties in P/M parts can be referred elsewhere [12-16]. But, the fatigue strength of hot forged and shot pinned P/M parts are detailed elsewhere [17, 18] and other stressed P/M parts can be further referred in literature [19-23]. Apart from these, the mechanical properties of differently produced ferrous based P/M steels of challenging in nature can be referred elsewhere [24-29].

Systems selected to be produced through elemental powders were (A) Fe-0.16%C, (B) Fe-0.16%C-0.70%Mn, (C) Fe-0.16%C-1.0%Cr-0.55%Mo, and (D) Fe-0.16%C-2.25%Cr-1.05%Mo steels. Applications of (A) category of steels i.e., Fe-0.16%C steels are that they are used for rivets, wires, nails, chains, stampings, seam welded pipes, hot and cold rolled strips, sheets and plates for general purposes, ship plates, boiler plates, cams and shafts, stay bolts, wheel hubs, brake housings and brake pedal levers. Since, B grades of steels, i.e., Fe-0.16%C-0.7%Mn steels contain 0.7%Mn which neutralizes the harmful effects of sulphur by forming MnS which melts at higher temperatures. Further manganese enhances the tensile strengths, imparts freedom from blow holes, deoxidizes the steel and produces fine grained steel and improves surface quality. Manganese can be used as structural materials as well. However, (C) grade of steels, i. e., Fe-0.16%C-1.0%Cr-0.55%Mo, and (D) grade of steels, i. e., Fe-0.16%C-2.25%Cr-1.05%Mo containing chromium and molybdenum as alloying elements which are known to induce beneficial effects to these steels. Chromium is added in steels as it is comparatively less expensive and imparts many useful characteristics to the steel. Readily combines with carbon in preference to iron. Cr offers resistance to oxidation. However, the addition of molybdenum in steels refines grains, enhances harden ability and improves high temperature properties. Thus, Cr-Mo steels possess good mechanical properties and sufficiently adequate machinability as molybdenum enhances the beneficial effects of chromium in chromium molybdenum steels and find applications as low alloy structural steels. These steels have good resistance to corrosion and oxidation and offer high creep resistance. Therefore, the above four steels have been selected for the present investigation. Basically, Cr and Mo are strong carbide formers. Cr raises tensile strengths, hardness, wears resistance and hardenability and makes the steel stainless when added beyond 12%. These steels find applications in general purpose structural applications such as ball bearing steels, spring steels, hard magnetic steels, and, stainless steels. Since, molybdenum is a strong carbide former, imparts high temperature strengths, enhances resistance to creep, minimizes temper embrittlement, and increases the resistance to corrosion of high chromium steels, and, therefore, molybdenum assists in case hardening steels, Hot work steels, High speed steels, and, Non magnetic steels.

Aim of the present investigation is to produce and evaluate the tensile properties of hot forged square cross section (~13mm x ~13mm) bars with an approximate lengths of 100±05mm of Fe-0.16%C, Fe-0.16%C-0.7%Mn, Fe-0.16%C-1.0%Cr-0.55%Mo,and, Fe-0.16%C-2.25%Cr 1.05%Mo steels prepared from elemental powders which were suitably mixed, homogeneously blended, compacted, sintered, hot forged to square cross-section bare and heat treated differently. Mechanical properties are suitably related to microstructure and SEM fractographs.

II. Experimental Details

2.1 Materials Required

Atomized iron powder of -180 um was procured from M/s. Sundaram Fasteners Pvt. Limited, Hyderabad, and Andhra Pradesh, India. Manganese, chromium and molybdenum powders of -37 um were obtained from M/s. The Ghrishma Speciality Powders Limited, Mumbai, Maharashtra, India. However, the graphite powder of less than 5 micron was supplied by the M/s. Ashbury Graphite Inc., New Jersey, U.S.A.

2.2 Tooling and Equipment

High-Carbon High-Chromium die steel was required to fabricate the mother die, punch, and the bottom insert for compaction of powder blends. Molybdenum-di-sulphide paste was needed to be used during compaction as a die wall lubricant. In house designed, fabricated die, punch and bottom insert were suitably heat treated and tempered. However, hot forging die set was fabricated from molybdenum hot die steel. These were suitably heat treated and tempered.

2.3 Powder and Powder Blend Characteristics

Basically, the ability of a metal powder blends to be effectively compacted and the resulting properties of the compacts before and after sintering are influenced to a substantial degree by the characteristics of the starting powdered material. The basic powder characteristics required to be assessed include, sieve size analysis, apparent density, flow rate and compressibility. Sieve size analysis of basic iron powder is given in Table 1, and, Table 2 shows the flow rates, apparent densities and the compressibility for iron powder and other powder blends to yield the final composition of Fe-0.16%C, Fe-0.16%C-0.7%Mn, Fe-0.16%C-1.0%Cr-0.55%Mo, Fe-0.16%C-2.25%Cr-1.05%Mo steels after sintering. Manganese, chromium and molybdenum powders taken in the present investigation were of -37 microns.

Table 1 Sieve Size Analysis of Iron Powder

Sieve size, µm	**Powder Size Distributio**								
Wt % retained	**-180 + 150**	**-150 +125**	**-125 +106**	**-106 +90**	**-90 +75**	**-75 +63**	**-63 +53**	**-53 +37**	**-37**
Wt% powder retained	**1.52**	**1.83**	**23.12**	**1.11**	**21.86**	**2.21**	**18.60**	**13.62**	**16.11**
Cum, Wt% powder Ret.	**1.52**	**3.35**	**26.47**	**27.58**	**49.44**	**51.65**	**70.25**	**83.87**	**99.98**

2.4 Powder Blend Preparation

Powder mixes of Fe-0.16%C, Fe-0.16%C-0.7%Mn, Fe-0.16%C-1.0%Cr-0.55%Mo and Fe-0.16%C-2.25%Cr-1.05%Mo were separately kept in a standard stainless steel pots with a powder mix to porcelain balls of 10 - 15mm diameter in the weight ratio of 1.1:1. Pot lids were securely tightened, and, the pots were fixed on the pot mill and the mill was switched on. The blending operation was carried out for a period of 32 hours which yielded homogeneous powder blends. Homogeneity of powder blends were ascertained by taking nearly 120±10 g of each of the powder mixes from each pot and were used for measuring the flow rates, and apparent densities. Immediately, after the completion of measurements of flow rates and apparent densities, the powder mixes were returned back to their respective pots, and, the pot lids were tightened once again and were placed back on the potmill and securely fixed and then the mill was switched on again, This operation was repeatedly carried out till the last thee consecutive readings of flow rates and apparent densities were almost constant independently. This ensured the homogeneity of the powder blends. Thus, the time of blending was experimentally found to be 32 hours and the same was fixed.

Table 2 Basic Properties of Iron, Fe-0.16%C, Fe-0.16%C-0.7%Mn, Fe-0.16%C-1.0%Cr-0.55%Mo and Fe-0.16%C-2.25%Cr-1.05%Mo Powder Blends.

Sl. No.	Systems	Apparent density, g/cc	Flow rate by Hall Flow Meter, S/100g.	Remarks
1	Iron	2.973	51.52	6.594g/cc at 400±10MPa
2	Fe-0.16%C	2.934	48.67	6.751g/cc at 450±10MPa
3	Fe-0.16%C-0.7%Mn	2.990	50.93	6.756g/cc at 375±10MPa
4	Fe-0.16%C- 1.0%Cr-0.55%Mo	3.010	47.01	6.74g/cc at 450±10MPa
5	Fe-0.16%C-2.25Cr -1.05%Mo	3.090	46.77	6.732g/cc at 375±10MPa

2.5 Compact Preparation from Iron powder and the Powder Blends

Green compacts of iron powder and the above prepared powder blends were prepared on a 1.0 MN capacity Universal Testing Machine. Compacts of initial aspect ratios of 1.34 with the diameter being 27.75mm were prepared by applying pressures in the range of 540±10 M Pa in the relative density range of 0.85±0.01of theoretical by taking accurately pre-weighed iron powder and powder blends respectively. In all, twenty four compacts of each composition were prepared. A schematic diagram shown in fig.1 depicts the compaction assembly for the compaction of iron powder and powder blends.

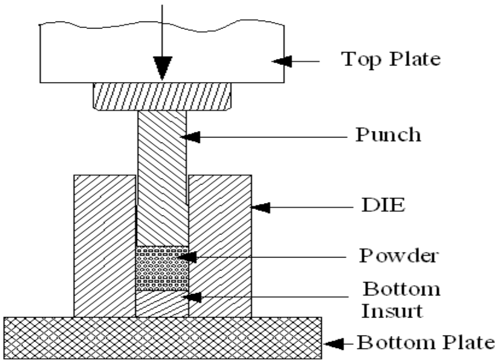


Figure 1 Complete Compaction Assembly - Schematic Diagram

2.6 Application of Indigenously Developed Ceramic Coating and Drying

Entire surfaces of all compacts of all compositions were coated with a thin film of indigenously developed ceramic coating [30] and the same was allowed to dry for a period of 12 hours under an ambient conditions. A second coat of the same coating was now applied on the entire surfaces of all the compacts once again, but, this time 90^0 to the previous coating. This second coating was also allowed to dry under the aforementioned conditions for a further period of 12 hours.

2.7 Sintering and Hot Forging To Square Cross-Section Bars

The ceramic coated compacts of all compositions were separately sintered in an electric muffle furnace in the temperature range of 1373±10K for a period of 120 minutes. The sintered compacts of H/D ratio of 1.34 with a diameter of 27.75mm were hot forged to square cross-section (13mmx~13mm) bars of approximate lengths of 100±5mm. Twelve forged bars of each compositions were kept inside the furnace chamber and homogenized for a period of sixty minutes at the sintering temperature itself, and, subsequently cooled to room temperature inside the furnace chamber by switching off the furnace. Apart from the above, other sets of twelve sintered compacts of each composition were also forged to similar types of bars and then quenched in linseed oil kept at room temperature separately.

III. Results and Discussions

3.1 Dimensional Measurements and Tensile Properties

Standard tensile specimens as per specifications given elsewhere [27] were machined from the Fe-0.16%C, Fe-0.16%C-0.7%Mn, Fe-0.16%C-1.0%Cr-0.55%Mo and Fe-0.16%C-2,25%Cr-1.05%Mo sintered powder metallurgy steels hot forged to square cross-section bars under two different conditons of heat treatments, namely, sintered hot forged and oil quenched (SFOQ) and sintered hot forged, but, homogenized at 1373±10K for sixty minutes and furnace cooled (SFHFC). Prior to conducting the tensile tests, the dimensional measurements such as initial gauge length (L_0), initial diameter (D_0) within the guage length were under taken and recorded. During and after fracture, the final gauge length (L_f) and final diameter (D_f) at the point of fracture were also measured and recorded. Further peak load (P_{pl}, Kg) qand fracture load (F_{fl}, Kg) were also recrded during and after carrying out the tensile tests respectively. All tension test experiments were carried out on a 0.02 MN capacity bench type Haunsfield Tensometer. Original area of cross-section (A_0, mm^2) for all specimens were calculated and all experimental and measured parameters are provided in Table 3. Perusal of this table very clearle reflects that the area of cross-section at the fracture point has decreased irrespective of the heat treatments meted out to the specimens and their compositions. Further the area of reduction in tension tested specimens were observed to be more when the

Table 3 Initial and Final Dimensions of the Tensile Specimens of Four Different Sintered Hot Forged P/M Steels to Square -Cross Section Bars

Steel Composition	Treatment	Dimensional measurement				Peak Load	Area of Cross section		Fracture Load
		L_0 mm	D_0 mm	L_f mm	D_f mm	P_{pl}, Kg	A_0	A_f	F_{fl} Kg
Fe-0.16%C	**SFOQ**	**5.17**	**3.74**	**6.67**	**3.18**	**761**	**10.96**	**7.94**	**724**
	SFHFC	**5.18**	**3.85**	**7.66**	**2.68**	**428**	**11.62**	**5.64**	**357**
Fe-0.16%C-0.55%Mo	**SFOQ**	**5.59**	**3.74**	**7.01**	**3.42**	**810**	**10.98**	**9.20**	**728**
	SFHFC	**5.73**	**3.76**	**7.76**	**3.00**	**486**	**11.08**	**7.08**	**342**
Fe-0.16%C-1%Cr-0.55%Mo	**SFOQ**	**6.07**	**3.75**	**6.5**	**2.54**	**769**	**11.04**	**9.85**	**738**
	SFHFC	**5.43**	**3.71**	**7.72**	**3.26**	**307**	**10.80**	**8.34**	**269**
Fe-0.16%C-2.25%Cr-1.05%Mo	**SFOQ**	**6.54**	**3.76**	**7.52**	**3.68**	**744**	**11.10**	**10.21**	**738**
	SFHFC	**7.19**	**3.72**	**8.56**	**3.34**	**394**	**10.88**	**8.69**	**375**

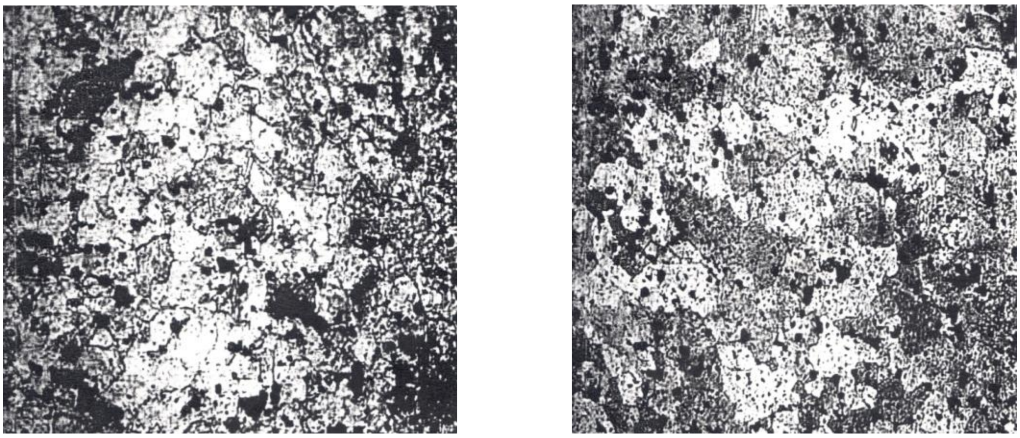
Specimens were subjected to homogenization step followed by furnace cooling. Apart from this, these specimens exhibited increased elongations compared to the specimens which were forged and directly quenched in oil. In order to justify the above, the Table 4 has been constructed based on the experimental data and standard calculations of tensile properties such as tensile strengths, fracture (true and engineering) strengths, per cent age elongation and per cent area reduction including true tensile and true area strains at fracture. Further, this table shows the hardness taken on each of the specimens under all conditions of heat treatments. Directly forged and oil quenched specimens have shown higher values of tensile strengths compared to the specimens which were forged, homogenized and furnace cooled. Apart from these, it is also observed that the forged-homogenized and furnace cooled specimens have demonstrated quite high values of ductility compared to the forged and oil specimens. An introduction of homogenization step for an hour at the sintering temperature followed by furnace cooling has resulted in a substantial drop in tensile strength with an enhancement in ductility, i.e., toughness. Similarly, the hardness values have also dropped correspondingly on homogenization.

Table 4 Calculated Tensile Properties of Four Different Hot Forged Low Alloy P/M Steel Bars

Steel Composition	Heat Treatments	Tensile Properties								
		T.S.	F.S. , MPa		%El.	Strain at Fract.		% A.R.	Area Strain $\ln(A_0/A_f)$	Hardness
			Engg	True		Engg	True			
Fe-0.16%C	**SFOQ**	**694.3**	**661**	**912**	**28.99**	**0.29**	**0.276**	**27.58**	**0.323**	**249**
	SFHFC	**368.5**	**307**	**633**	**47.69**	**0.477**	**0.515**	**51.46**	**0.723**	**161**
Fe-0.16%C 0.7%Mn	**SFOQ**	**738**	**663**	**792**	**25.34**	**0.253**	**0.162**	**16.23**	**0.177**	**256**
	SFHFC	**438.7**	**309**	**483**	**35.43**	**0.354**	**0.361**	**36.10**	**0.448**	**169**
Fe-0.16%C-1%Cr-0.55%Mo	**SFOQ**	**697**	**669**	**749**	**7.03**	**0.070**	**0.108**	**10.76**	**0.0680**	**269**
	SFHFC	**284**	**248**	**323**	**42.17**	**0.422**	**0.228**	**22.79**	**0.259**	**157**
Fe-0.16%C-2.25 %Cr-1.05%Mo	**SFOQ**	**670**	**665**	**723**	**14.93**	**0.149**	**0.080**	**7.95**	**0.083**	**287**
	SFHFC	**362**	**345**	**431**	**23.22**	**0.232**	**0.201**	**20.11**	**0.224**	**251**

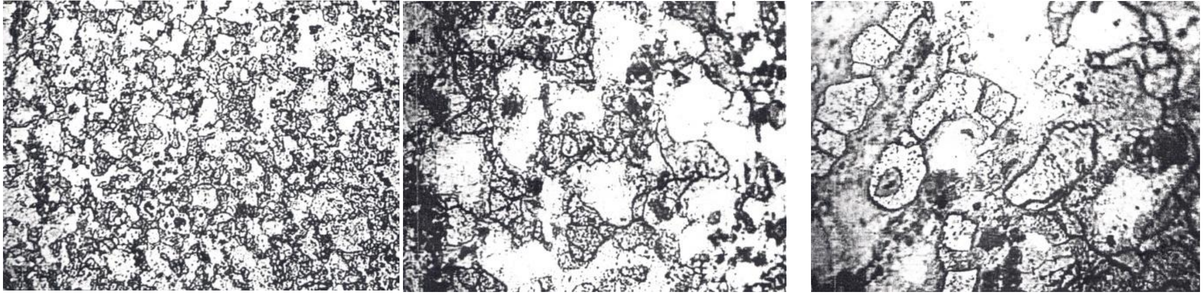
3.2 Microstructural Details

Figs. 2, 3, 4, 5, 6, 7 and 8 are shown as the metallographs exhibiting the microstructural details of Fe-0.16%C, Fe-0.16%C-0.7%Mn, Fe-0 .16%C-1.0%Cr-0.55%Mo, and Fe-0.16%C-2.25%Cr-1.05%Mo steels processed using elemental powders which were homogeneously blended, compacted, suitably coated with the indigenously developed ceramic coating to protect them during sintering were sintered, and, then hot forged to square cross-section bars. Equal numbers of these bars were oil quenched and homogenized for a period of one hour at the sintering temperature itself and then furnace cooled. Microstructures have well corresponded to the tensile properties that are revealed from the tensile test results. Fig. 2 shows the microstructures which are mostly ferrite with few fine pores uniformly distributed. These microstructures correspond to as forged, homogenized and furnace cooled condition. Whereas, the fig. 3, represents the structure of the same steel under the condition of sintered, forged and oil quenched condition. Similarly figs. 3(a), (b) and (c) are shown from three different locations of the hot forged, but, homogenized and furnace cooled condition showing mostly ferrite and few scattered but rounded pores well within the structure itself. However, fig. 4 represents the same steel under the as forged and oil quenched condition. Similarly figs. 5 and 6 correspond to Fe-0.16%C-1.0%Cr-0.55%Mo steel under two above mentioned conditions. Likewise figs. 7(a), 7(b) and 7(c) and fig.8 correspond to the P/M steel of composition Fe-0.16%C-2.25%Cr-1.05%Mo under the above conditions, i.e., under the forged, homogenized and the furnace cooled condition. and also under the forged and oil quenched condition. The general observations of these micro-structures reveal that the homogenization step has introduced grain growth and structural modification. These structures clearly show that they are under the completely stress relieved condition. These structures very closely corresponded to the tensile properties as well as the respective hardness values. Further observation reveals that the microstructure of forged and homogenized specimens contain rounded and evenly distributed pores, but, they are very few in numbers whereas, the microstructure corresponding to forged and oil quenched conditions did exhibit the presence of rounded pores but unevenly distributed in the microstructure. Apart from these, the steels containing chromium and molybdenum have shown carbide formation and also at few places un-dissolved chromium and molybdenum particulate structures are evidently seen. Such particulate structures are seen in both types of heat treated specimens.



(a) SFHFC CONDITION(2% Nital) Mag. 250X **(b)SFOQ CONDITION (2% Nital) Mag. 250X**

Figure 2 Microstructures of Sintered Forged Fe-0.16%C Steel Under Two different Heat Treated Condition (etchant; 2% Nital)



(a) Centre(100X)

(b) Middle of centre and edge(100X) **(c) Edge(100X)**

Figure 3 Microstructures shown at Three Different Locations of the Cross-section Bars of Fe-0.16%C-0.7%Mn P/M Steel SFHFC Condition (etchant; 2% Nital)

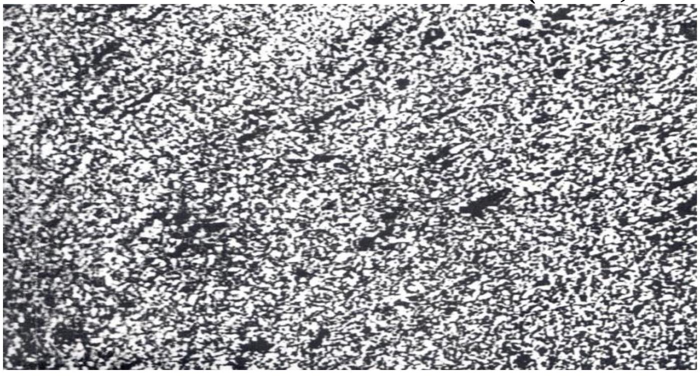
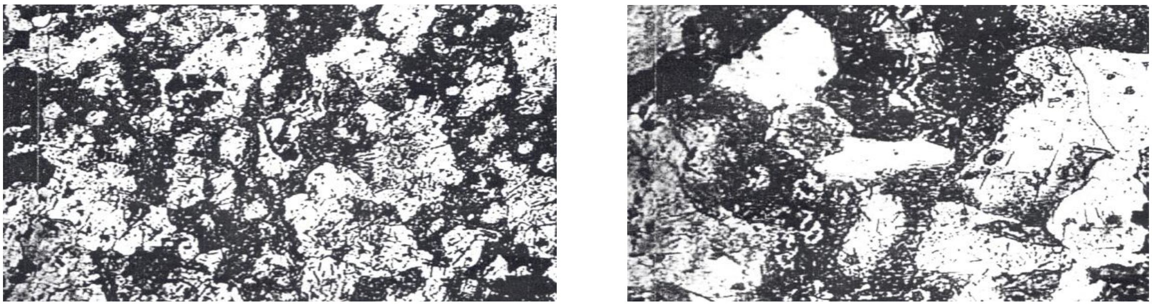
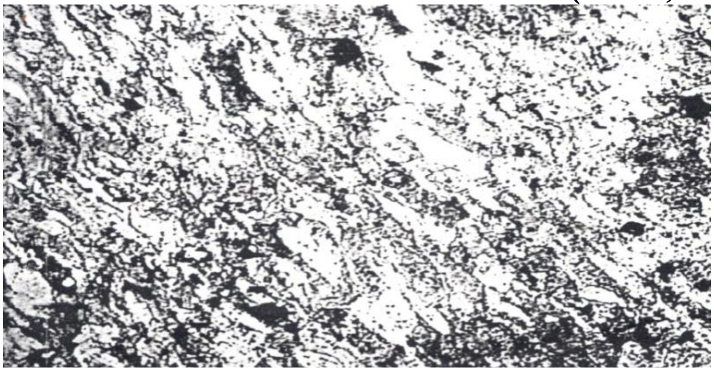


Figure 4 Microstructures shown at the Centre Locations of the Cross-section Bar of Fe-0.16%C-0.7%Mn P/M Steel SFOQ Condition at 250X; (etchant; 2% Nital).



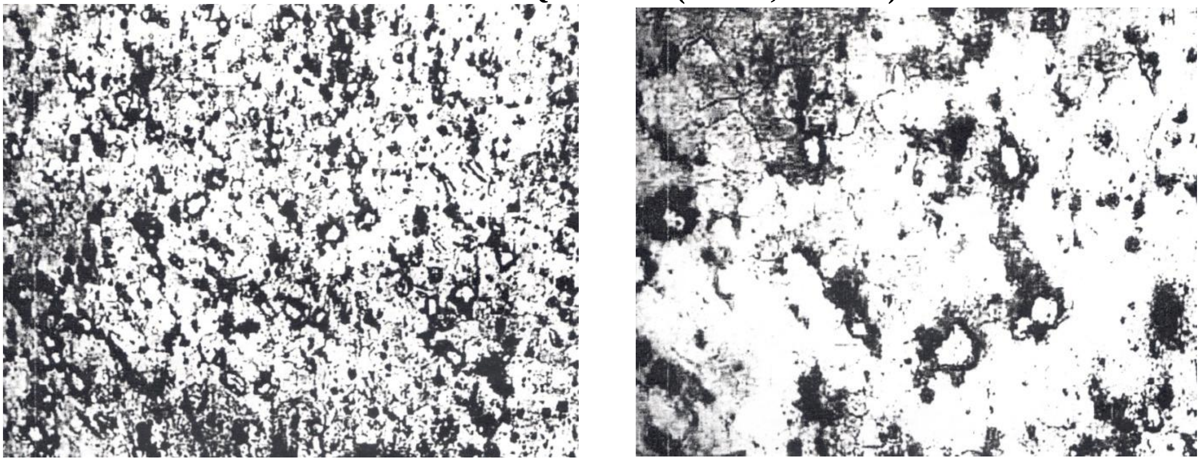
(a) Centre(250 X) (b) Edge(250 X)

Figure 5 Microstructures shown at the Centre and at the Edge Locations of the Cross-section Bar of Fe-0.16%C-1.0%Cr-0.55%Mo P/M Steel SFHFC Condition (etchant; 2% Nital)



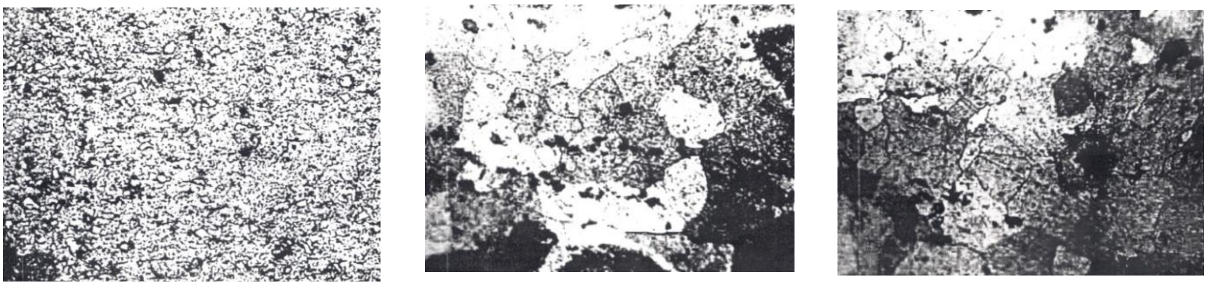
Magnification = 100X

Figure 6 Microstructures shown at the Centre Locations of the Cross-section Bar of Fe-0.16%C-1.0%Cr-0.55%Mo P/M Steel SFOQ Condition (etchant; 2% Nital).



(a) Centre(100 X) (b) Edge(100 X)

Figure 7 Microstructures shown at the Centre d at the Edge Locations of the Cross-section Bar of Fe-0.16%C-2,25%Cr-1.05%Mo P/M Steel SFHFC Condition (etchant; 2% Nital)

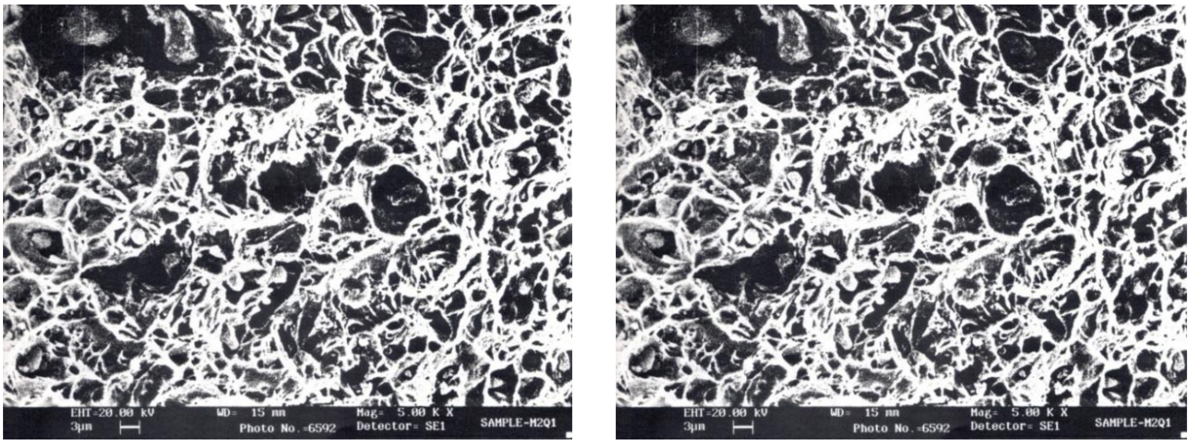


(a) Centre(400X) (b) Middle of centre and edge(400X) (c) Edge(400X)

Figure 8 Microstructures shown at the Three DifferentLocations of the Cross-section Bar of Fe-0.16%C-2.25%Cr-1.05%Mo P/M Steel Under SFOQ Condition (etchant; 2% Nital).

3.3 SEM Fractography Fractured Surfaces of Tensile Tested Specimens all four Steels Investigated

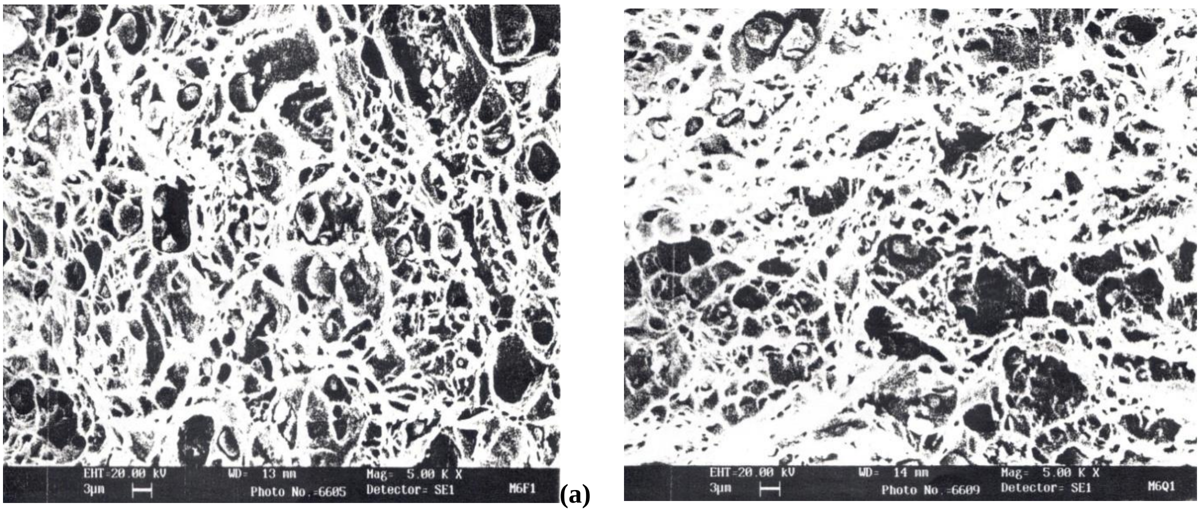
Fractographs shown through figs. 9 to 12 reveal the exact nature of the fractured surfaces of the tensile tested specimens under various conditions. Fig. 9 (a) shows the fractographs corresponding to Fe-0.16%C P/M steel which has been homogenized and furnace cooled. This structure clearly shows large number of dimples indicating the failure mode to be highly ductile and the same is very well supported by the tensile properties that are fairly high, which is an index of high ductility (~48%elongation and ~52% area reduction). Similarly the fractographs represented through fig. 9 (b) also depicts fairly large number of dimples and at places fine, but, rounded porosities in good numbers are also visible. Fractured pieces of this specimen when visually examined have exhibited cup and cone type separation of the two corresponding counter parts. High level of ductility (29% elongation and 28% area reduction) is recorded. Similarly the steel corresponding to Fe-0.16%C-0.7%Mn composition exhibited quite ductile mode of failures under both the conditions of heat treatments.However, under the homogenized and furnace cooled condition the failure has advanced through the coalescence of residual pores, but, the failure remained ductile only (fig.10(a). Once again the similar situation existed when the steel has been forged and oil quenched. Even though, the steel exhibited high strength values, the ductility remained fairly high indicating that the steel under this condition also remained fairly tough and thus the failure remained quite ductile as is evident through the fig.10(b).



(a) SFHFC **(b) SFOQ**

Figure 9 SEM Fractographs of Tensile Tested Specimen fractured Surfaces of Fe-0.16%C P/M Steel

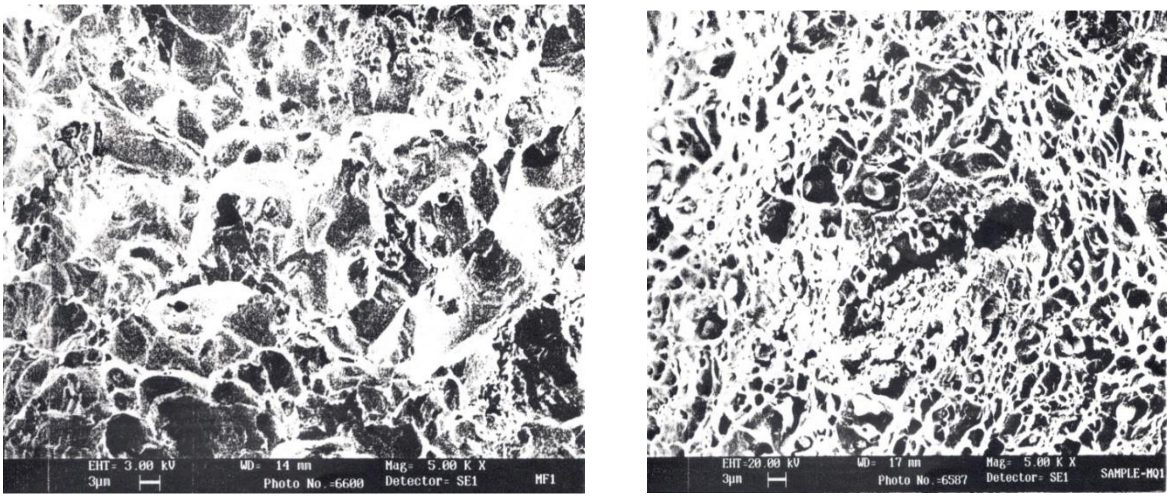
Figs. 11 and 12 showing the SEM fractographs corresponding to the steel composition of Fe-0.16%C-1.0%Cr-0.55%Mo. This steel SEM fractographs under the forged, homogenized and furnace cooled condition shows large number of dimples an index of ductile mode of failure (fig. 11(a)) which is ably supported by the tensile test results exhibiting high percentage of elongation (~42%) and per cent area reduction (~23%).SEM fractographs shown in fig. 11(b) corresponds to the same steel, but, under sintered, forged and oil quenched condition. Even though dimples



(a)

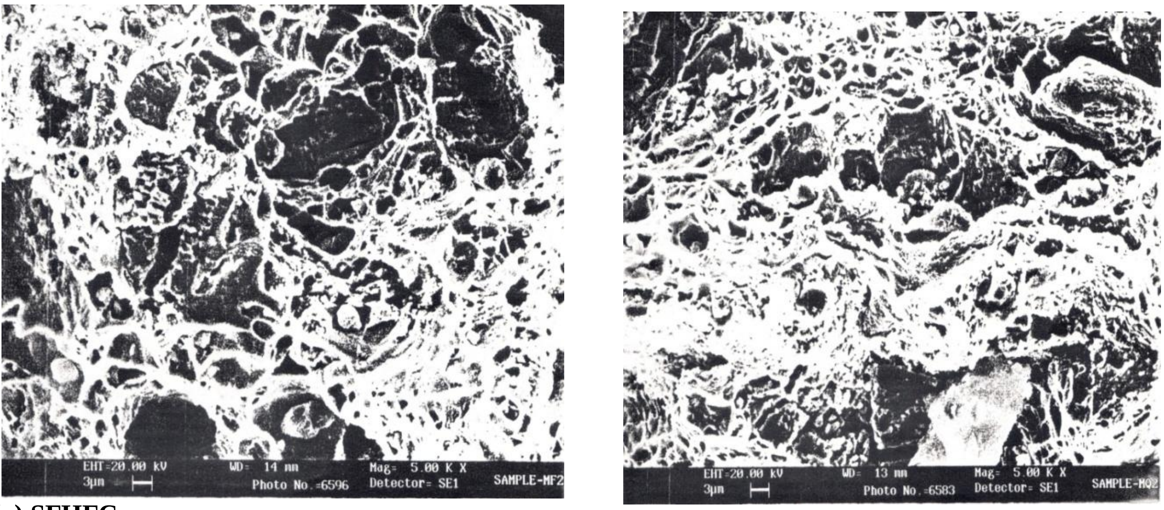
SFHFC **(b)SFOQ**

Figure 10 SEM Fractographs of Tensile Tested Specimen fractured Surfaces of Fe-0.16%C-0.7%Mn P/M Steel Under Two conditions of Heat Treatments.



(a) SFHFC (b) SFOQ

Figure 11 SEM Fractographs of Tensile Tested Specimen fractured Surfaces of Fe-0.16%C-1.0%Cr-0.55%Mo P/M Steel Under Two conditions of Heat Treatments.



(a) SFHFC

(b) SFOQ

Figure 12 SEM Fractographs of Tensile Tested Specimen fractured Surfaces of Fe-0.16%C-2.25%Cr-1.05%Mo P/M Steel Under Two conditions of Heat Treatments.

IV. Conclusions

Based on the experimental data on tensile properties of four different low alloy steels produced through powder metallurgical routes using elemental powders via homogeneous blending, compacting, sintering and hot forging to square cross-section bars and heat treating them under two distinct conditions such as sintering, forging and oil quenching (SFOQ) and sintering, forging and homogenizing at the sintering temperature for a period of an hour followed by cooling them inside the furnace itself and after analyzing the data critically, the following main conclusions have emerged:

1. Four P/M steels investigated in the present investigation produced from the elemental powders which were sintered, forged and oil quenched have shown improved strengths, but, reduced ductility compared to the steels which were sintered, forged, homogenized and furnace cooled which have shown high degree of ductility,
2. Microstructures of all the four steels have clearly shown the presence of porosities which were mostly rounded in the event of homogenized for a period of one hour at the sintering temperature and cooling inside the furnace itself. However, at places in the microstructures corresponding to steels containing chromium and molybdenum, few un-dissolved particles of these elements are also present,
3. Tensile tested specimens fractured in a cup and cone type in all the steels except for the steel Fe-0.16%C which was highly cup and cone type when they were homogenized and furnace cooled. However, the forged and oil quenched specimens have exhibited mixed mode of failures,

4. SEM fractographs corresponding to steels which were produced by sintering, forging, homogenizing and furnace cooling have exhibited mostly ductile failures as it contained large number of dimples which are an index of ductile failures, but, the quenched steels in their corresponding fractographs have shown fairly good amount of dimples as well as presence of particle de-lamination which is an index of mixed mode of failures,

Finally summarizing the outcome of the present investigation, it is, established that there exists a certainty of producing the quality P/M products by using elemental powders and their homogeneously blended mixes to required compositions of the given steel/s. The higher mechanical properties such as strength and sound metallurgical structures along with the enhanced toughness under the sintered forged and oil quenched condition. However, under sintered, forged, homogenized and furnace cooled condition, the strength and toughness attained are suitable for producing quality structural parts. Thus, the present investigation opens up a new area of research to produce structural components using elemental powders.

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