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Deformation and Densification Response of Sintered Ni-Mo Low Alloy Steels during Cold and Hot Working

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ABSTRACT

Background: This paper entities the deformation and Densification behavior of sintered Powder Metallurgy low alloy steels. **Objective:** The present research work pertains to the study of the densification behaviour of sintered low alloy P/M steels containing Ni and Mo during cold & hot deformation processing and cold repressing. Elemental powders of atomized iron, graphite, nickel and molybdenum were mixed in suitable proportions using a ball mill, compacted and sintered in order to yield the following alloy compositions: Fe-0.2 % C, Fe-0.2 % C-2 % Ni, Fe-0.2 % C-2 % Ni-1.5 % Mo and Fe-0.2 % C-2 % Ni-3 % Mo. The compaction was performed in a 1000 kN hydraulic press using suitable cylindrical die-punch combination and graphite lubricant. Sintering of the ceramic-coated cylindrical preforms was carried out at 1000 ± 100 C in a muffle furnace for a period of 120 minutes. Cold upsetting, hot upsetting and cold repressing studies on the sintered preforms were undertaken in order to study the densification and plastic deformation behaviour of the low alloy P/M preforms under various applied loads. Further, microstructural analysis was carried out on the cold upset forged, hot upset forged and cold repressed alloy samples in order to correlate the plastic deformation and densification characteristics with the metallurgical structure of the sintered and forged alloys. **Results:** It has been observed that the plain carbon steel preforms exhibit better densification and deformation behaviour. The densification and deformation behaviour of the alloy preforms containing 2 % Ni and 2 % Ni-1.5 % Mo was intermediate to that of the plain carbon steel and Fe-0.2%C-2 % Ni-3 % Mo steel preforms. The addition of Ni and Mo resulted in reduced levels of deformation as well as densification, irrespective of the mode of deformation. Further, the microstructures of Ni based alloy preforms show some austenite phase and the Mo based alloy preforms have distributed Mo particulates in their microstructure. **Conclusion:** Therefore, it is contended that the presence of retained austenite phase and Mo particulates in the microstructure strongly influences the deformation behaviour of the alloy preforms.

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INTRODUCTION

The pores present in pressed and sintered products are one of the major factors affecting the mechanical properties of P/M alloys to a lower value compared to conventional wrought materials. The removal of voids is possible by post sintering operations such as cold upsetting, hot upsetting, cold repressing extrusion etc. The maximum possible density of the sintered P/M parts plays a vital role in the performance and life of the components. These pores are sites of weakness and act as origins of crack initiation in sintered materials. The sintered density, pore distribution and size, aspect ratio of the preforms etc., are the main parameters for the P/M preform characteristics during post sintering operations. The densification and deformation of the alloy preforms also depends on the alloying element, alloy types and the microstructural phases formed during sintering and post sintering operations. These densification and deformation of the alloy preforms due to the addition of different alloying elements to the plain carbon steel will be very much useful for the designer to select an appropriate material for a particular structural, automotive and other applications. The present study focuses on the densification & deformation behaviour of P/M steels by varying the deformation types such as cold upsetting, cold repressing, hot upsetting, flow stress and alloying elements. Several researchers have explored the influence of several factors such as types of powders, alloy addition, sintering conditions, post sintering heat treatment, resintering and repressing cycles and nature of deformation on the properties of sintered ferrous P/M alloys.

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Danninger *et al* (1993) reviewed the existing literature on the relationship between microstructure and mechanical properties mechanical properties and microstructure of P/M alloys. Danninger *et al* (1993), in their studies, have concluded that both compacting pressure and sintering parameters influence the mechanical properties of sintered alloy steels. Haynes (1989) pointed out that the strengthening of sintered P/M low alloy steels can be achieved through densification, alloying and heat treatment. Amador and Torralba (2003), in their investigations on P/M Ni steels, have shown that P/M steels produced from pre-alloyed powders possess mechanical properties similar to steels alloyed with elemental powders. Hence the present research work is carried out with admixed elemental metal powders subjected to single pressing and sintering operation.

The most widely used alloying elements in sintered alloy steels are Cr, Ni, Cu, Mo, Si and C, which have low affinity for oxygen. Several researchers have attempted studies on P/M alloy steels containing these elements. Chandramouli *et al* (2006) observed that the sintered and forged Fe-1 % C steel undergoes higher densification during forging compared to pure Fe. Shanmugasundaram *et al* (2008) studied the influence of Ni and Cr on densification and deformation of P/M steels and concluded that Ni and Cr influence the densification and deformation. In the present study, the focus is mainly on the influence of Ni & Mo as alloying elements on the deformation & densification behaviour. Youseffi *et al* (2000) studied the sintering, microstructure and mechanical properties of P/M Mn- Mo steels and reported that the sintered microstructures are sensitive to cooling rates. According to the findings of the above-mentioned authors, Mo has been identified as having beneficial effect on the properties of the steels studied. The influence of microstructure on impact and wear behaviour of sintered Cr and Mo steels has been studied by Molinari *et al* (1999). Youseffi *et al* (2002) carried out a study of the microstructures of Fe-1.5 % Mo P/M alloys with addition of elemental silicon, ferro silicon and graphite and found that the sintered microstructure consists mainly of fine or coarse pearlite, bainite, martensite and some retained austenite with hardness in the range of 250 -720 HV10.

In view of the emerging importance of low alloy P/M steels in automotive parts application such as bushes, valve inserts, valve seats etc., and due to their potential high strength and economic production, the authors have undertaken the deformation and densification behaviour of Ni-Mo low alloy P/M steels with 0.2 % graphite. The microstructures of the forged alloys have also been correlated with the densification behaviour.

Experimental Details:

Atomized iron (Fe) powders of particle size of -150 µm supplied by M/s Hoganas India Ltd., Pune and graphite powder of particle size 5 µm supplied by M/s Ausbury Graphite Mills, USA, Nickel (Ni) Powder of -100 µm and Molybdenum (Mo) powder of -100 µm were used for the present research work. Required mass of Fe and other elemental powders such as C, Ni and Mo were accurately weighed and mixed in a pot mill for 10 hours in order to achieve homogenization of the powder mix. The blended powder mix yielded the following composition by mass of alloys namely, Fe-0.2 % C, Fe-0.2 % C-2 % Ni, Fe-0.2 % C-2 % Ni-1.5 % Mo and Fe-0.2 % C-2 % Ni-3 % Mo which are close compositions of conventional wrought steels. The blended powder mix was then compacted into cylindrical billets of aspect ratio (height/diameter) of 0.5 using a hydraulic press of 100 tons (1000kN) capacity, applying the required pressure. Graphite mixed with lubricating oil was used as a lubricant. Immediately after the compaction, an indigenously developed aluminium based ceramic coating was applied on the surface of the compacts and dried for 24 hours, in order to prevent oxidation of the compacts during sintering. Sintering of the coated samples was carried out in a muffle furnace of 3.5 kW capacity at a temperature of 1000 ± 10^0 C for a period of 120 minutes. During cold upsetting, hot upsetting and cold repressing, the initial sintered preforms density values were fixed in the range 82 ± 2 % in order to restrict the influence of prefroms density on densification of the alloys under study. Cold upsetting of the sintered preforms was carried out in a hydraulic press of 100 tons capacity using a set of flat dies and lubricating oil mixed with graphite as a lubricant. Cold repressing of the sintered preforms was performed using the same die set used for compaction. The axial load was applied on the P/M preforms at the rate of 100kN/min during cold upsetting and cold repressing. Hot upsetting of the sintered preforms was carried out immediately after the sintering process, using a 200 tons (2000kN) friction screw press. Impact loads were applied at varying degrees, at constant ram speed (0.2 m/s), in order to introduce varying levels of axial deformations on the preforms. Dimensional and density measurements were accurately carried out after each step of cold upset, cold repress and hot upset deformations. Archimedes's principle was used to find the actual densities of the preforms after each step of deformation. The axial upsetting was continued up to the point of formation of fine surface cracks on the outer circumference. In the case of cold repressing, the axial applied load was restricted to 650 kN due to the increased material resistance as well as material back flow. The microstructures of the plastically deformed preforms to the maximum level were observed in a KYOWA, ME-LUX2, microscope fitted with CCD camera, interfaced with a computer and image analyser, employing standard procedure of specimen preparation.

RESULTS AND DISCUSSIONS

The axial applied stress during each step of cold deformation of the P/M sintered cylindrical preforms had been evaluated accurately from the values of axial applied load and the contact area of the cylindrical preforms. The axial true height strain was calculated from the values of the original un-deformed height and deformed height of the deformed cylindrical preforms. The dimensions of the deformed preforms were measured accurately using a digital vernier with two decimal places accuracy. The density of preforms after deformation was found out using Archimedes's principle. The evaluated values of the percentage theoretical density, axial applied stress, and true height strain were correlated to study the deformation characteristics and densification behaviour of the sintered alloy preforms. The axial applied stress was correlated with the true height strain values of the cold deformed and cold repressed preforms. The axial stress was also correlated with the percentage theoretical density for the cold deformed and cold repressed preforms. The percentage theoretical density of preforms was correlated with the true height strain for the specimens subjected to cold, hot deformation and cold repressing. Microstructures of the deformed alloys have been correlated with the deformation and densification behaviour.

Stress vs. true height strain:

During cold working of porous material the pores as well as the matrix material get deformed. As a result the flow stress as well as the strain depends on the initial porosity of the preform as well as the pore flattening effect during the deformation processes. The effect of pore shrinkage and deformation results in geometric hardening of the material, which further influences the material flow, densification and the final density attained during the forging process. In this context the densification of a sintered material is very much influenced by the flow stress, axial strain, and the mode of deformation during the post-sintering processing.

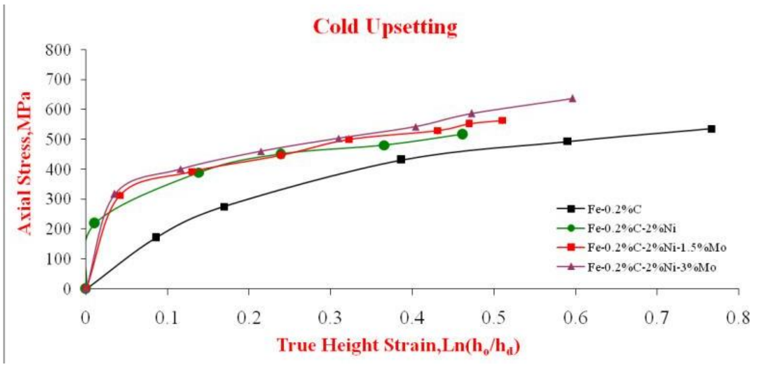


Fig. 1: Plots of Axial Stress versus True Height Strain of Sintered and Cold Upset

Fe-C-Ni-Mo Alloy Preforms:

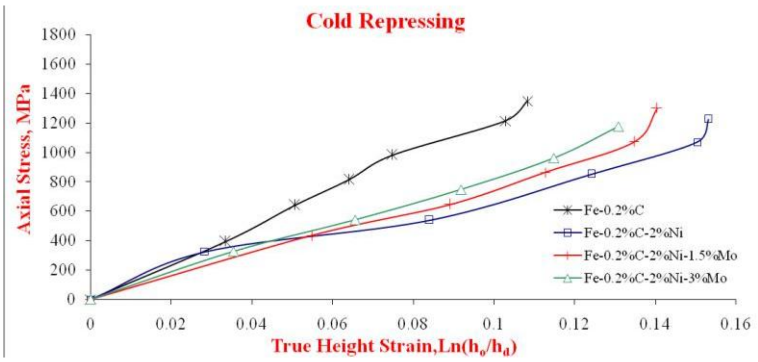


Fig. 2: Plots of Axial Stress versus True Height Strain of Sintered and Cold

Repressed Fe-C-Ni-Mo Alloy Preforms:

The deformation behaviour of the alloy performs undertaken for the present research work is depicted in fig.1, by plotting graphs of applied stress versus true height strain during cold upsetting. It is clearly evident from the graphs that the axial deformations of cylindrical preforms, irrespective of the type of alloy, exhibit two distinct stages of deformation. The first stage of deformation is characterized by a steep increase in applied stress with the corresponding levels of axial deformation being the lowest. This is due to the material hardening effect as a result of pore shrinkage, which leads to enhanced stress absorption. In the second stage, the axial strain on the preforms increases almost linearly with the applied stress. The axial stress to be applied for a given level of plastic deformation is found to be the highest in the case of the sintered Fe-C-Ni-3% Mo steels, followed by sintered Fe-C-Ni-1.5% Mo steel preforms. Further, the alloy containing 2%Ni alone is observed to undergo the lowest amount of axial strain namely, about 0.46 at an axial stress level of 520 MPa. Therefore it is evident that the alloy Fe-0.2%C-2% Ni is showing the least tendency to deformation under cold upsetting. Comparatively larger axial strains are observed for the alloy with additions of either 1.5% Mo or 3% Mo to Fe-0.2% C-2% Ni. Further, these two alloys also exhibit a similarity in their stress-strain behaviour. Mo addition higher than 1.5% is found to induce higher levels of axial deformation during cold upsetting. In general, the plain carbon steel with 0.2 % C shows the highest level of axial strain and therefore, tends to undergo larger levels of plastic deformation.

The axial deformation of the cylindrical alloy preforms under various levels of applied axial stress during cold repressing is represented in fig.2. Axial stress-strain behaviour is observed to be linear, irrespective of the type of alloy during cold repressing. Due to the restraint exerted on the lateral flow of both material and pores during axial pressing, a constant rate of increase in true axial strain is observed. Pores however have a tendency to get deformed sluggishly during repressing. Rounding of the small pores as well as increase in percentage theoretical density during the course of deformation impose an increase in resistance of the material to plastic deformation. The flow stress of the alloy preforms increases steeply during the end stage due to the presence of finer pores in the preforms, which are very difficult to flatten or eliminate. The above-mentioned trend in axial deformation is common to all the alloys considered for the present investigation. Largest axial strain has been undergone by Fe-C-2 % Ni alloy preform followed by Fe-C-Ni-1.5 % Mo and further by Fe-C-Ni-3 % Mo. Uniform distribution of Mo particles throughout the matrix as well as along the grain boundaries as shown in the microstructure (Fig. 10 and 11), would have prevented the coalescence of pores, resulting in the retention of fine rounded pores. Rounding of pores will be visible in the cold repressed preforms, by comparing the microstructures of as sintered, cold forged and cold repressed, and cold repressed preforms.

It was observed [11] that, the relationship between axial flow stress and true height strain for the preforms must follow a power law expression of the form:

$$\sigma = K\, \varepsilon^{n} \qquad (1)$$

Where, ‘σ’ is axial stress, ‘ε’ is true height strain, ‘K’ is stress constant and ‘n’ is work hardening exponent. The work hardening exponent ‘n’ is the major influencing factor for the plastic deformation. Hence, the study of the influence of alloy additions on the work hardening exponent of various steels has been carried out. The exponent has been obtained by fitting the experimental data in the form of power law equation. The corresponding R^2 values have been observed which are between 0.97 - 0.998 for all the alloys under consideration for the present research. Such high R^2 values indicate near perfect fit between stress-strain.

Stress vs. percentage theoretical density:

The plots of axial applied stress and percentage theoretical density of the alloys chosen for the present research are exhibited in fig.3 and 4 for cold upsetting and cold repressing respectively. It is observed from the densification curves shown in figure 3, that during cold upsetting the densification process of the alloy preforms proceed in two distinct stages. During the initial stages, the densification rate is low with a steep rise in applied stress values. After attaining a certain level of density, namely, 84 ± 1%, under an axial flow stress of 350 ± 50 MPa, the preforms undergo a linear increase of density with the flow stress. The plain carbon P/M steel exhibits the largest level of densification under comparatively lower levels of applied stress. The highest density attained by the plain carbon steel preform is about 94% of theoretical density, whereas the other alloys attained densities below 92% of the theoretical density. The alloys containing nickel show the least densification. The highest density attained in these alloys is about 89.5%. Beyond this stage of densification, fine surface cracks originate. The free surface cracks were found to be inclined at about 45^0 with respect to axial direction. Further, addition of Mo to Fe-C-2% Ni enhances the densification rate. Addition of higher percentage of Mo to Fe-0.2% C-2% Ni enhances the densification rate, further and the peak density attained is also improved to a maximum extent of about 92%. The difference in densification between 1.5%Mo and 3% Mo steel during cold upsetting is quite marginal, though 3% Mo alloy absorbs higher stress for the attainment of the same density level. Addition of the alloying element Ni alone to plain carbon steel lowers the plastic deformation as well as the percentage theoretical density. The presence of numerous fine and rounded pores, both intergranular and transgranular, leads to the poor plastic deformation and densification. This makes fine cracks at the circumference even at 350 kN of applied load. Mo is a known ferrite stabilizer. The improved plastic deformation of the Mo alloyed steels may be attributed to the soft ferritic structure. Presence of Mo particulates along the grains and grain boundaries appear to promote the ability of the Mo alloyed steel to withstand up to 490 kN. The densification behaviour of the alloys during repressing is observed to be linear with the plain carbon steel preform attaining the highest density followed by the Ni-Mo alloyed steels and Ni alloyed steel as observed in fig.4. It can be inferred from the plots that the cold repressing involves much higher levels of applied stress for the realization of a given density irrespective of the type of alloy. The totally constrained lateral flow of material and pores in repressing led to the requirement of higher flow stress. In general, the densification in the case of the alloy steel preforms during repressing is found to follow similar pattern. It is clearly evident that the maximum densification is attained during cold repressing due to the flow constraints imposed by the die walls, which leads to the full utilization of flow stress for densification. Both cold upset and cold repressed plain carbon steel preforms have undergone highest levels of densification. Addition of 2%Ni to plain carbon steel lowers the densification compared to the other alloys during cold upsetting. The reduction in densification of Mo alloyed steel preforms can be attributed to the presence of hard Mo carbide particulates. Referring to figure 4, it is inferred that, there is 6% reduction in densification for the same level of applied axial flow stress is noticed due to the addition of both 2% Ni and 3% Mo. In comparison with cold upsetting, the flow stress for cold repressing is almost doubled for the attainment of the same level of percentage theoretical density, irrespective of the alloy.

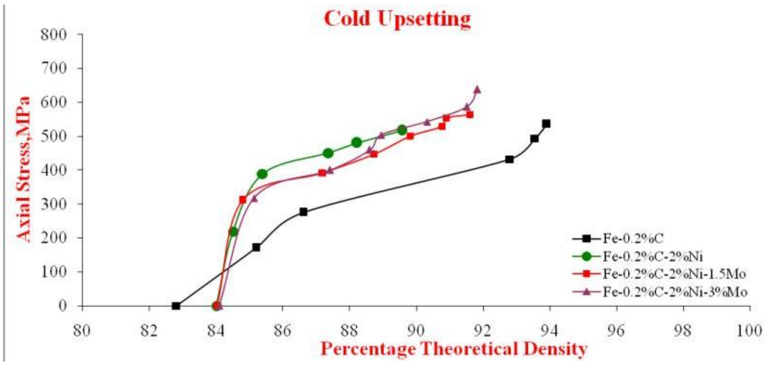


Fig. 3: Plots of Axial Stress versus Percentage Theoretical Density of sintered and*Cold Upset Fe-C-Ni-Mo Alloy Preforms.*

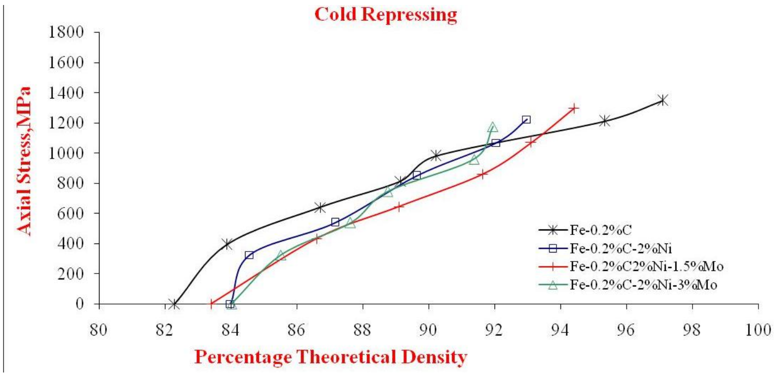


Fig. 4: Plots of Axial Stress versus Percentage Theoretical Density of sintered and Cold Repressed Fe-C-Ni-Mo Alloy Preforms.

Percentage theoretical density Vs true height strain:

The plots between the percentage theoretical density and true axial strain during cold upsetting, hot upsetting and cold repressing of the alloys selected for the present research are shown in the Fig.5, 6 and 7 respectively. These plots represent the densification of the cylindrical alloy preforms under varying levels of axial deformations during cold upsetting, cold repressing and hot upsetting respectively. The plots exhibit similarity of trend under both cold and hot upsetting tests. In hot upsetting (fig.6), the rate of increase in density is lower. The densification vs. deformation plots of the cold upset preforms, shown in fig.5, indicate that the plain carbon steel preforms exhibit the highest deformation as well as densification compared to the other alloys.

Addition of 2%Ni to plain carbon steel leads to a marginal reduction in densification & deformation about 30 %, in comparison with carbon steel. Addition of either 1.5% or 3 %Mo to Fe-0.2%C-2%Ni shows similarity in deformation and densification trends and also an increase in densification. The addition of higher quantity of Mo to Fe-0.2%C-2%Ni leads to higher levels of deformation, but almost no change in the maximum density levels. The densification and deformation plots of cold repressed preforms, shown in fig.7, exhibit that the plain carbon steel preforms undergo a maximum densification with lower levels of deformation due to the constraints imposed by the die walls during cold repressing. Addition of 2%Ni to plain carbon steel preforms undergoes a maximum axial strain. Further addition of 1.5% Mo to Fe-0.2%C-2%Ni shows a slight reduction in deformation. Addition of higher quantity of Mo namely 3% Mo also shows a reduction in deformation, which can be attributed to the presence of large number of Mo particles in the grain and along grain boundary. It is concluded that addition of the alloying element Ni and Mo influence to enhance the axial deformation. There is no significant densification enhancement noticed. During hot upsetting (fig.6), maximum deformation and densification is achieved in the plain carbon steel preforms. Addition of alloying element such as 2%Ni to plain carbon steel preforms, 1.5% Mo to Fe-0.2%C-2%Ni and 3%Mo to Fe-0.2%C-2%Ni shows similarity in the deformation and densification behaviour though at lower levels than the plain carbon steel preforms.

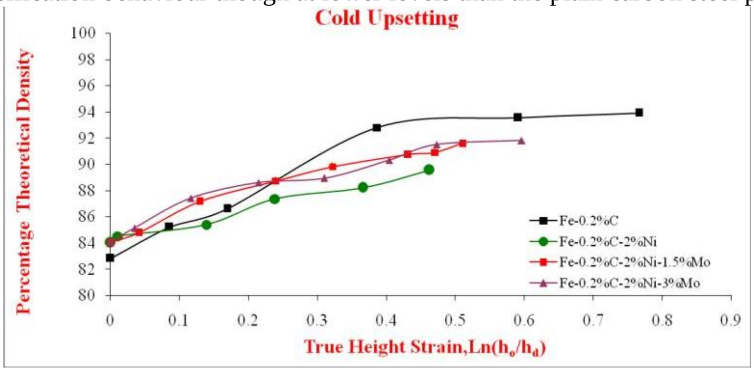


Fig. 5: Plots of Percentage Theoretical Density versus True Height Strain of Sintered and Cold Upset Fe-C-Ni-Mo Alloy Preforms.

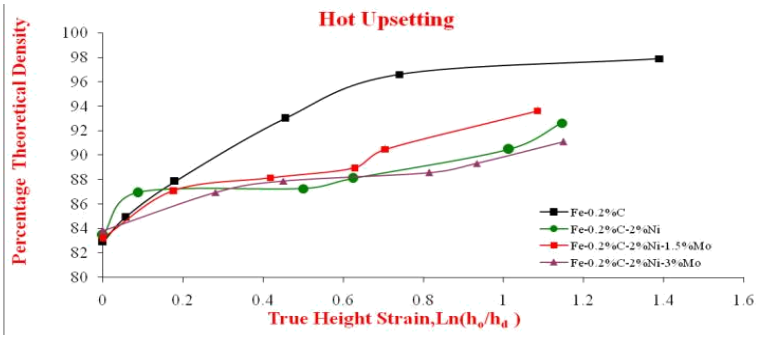


Fig. 6: Plots of Percentage Theoretical Density versus True Height Strain of Sintered and Hot Upset Fe-C-Ni-Mo Alloy Preforms.

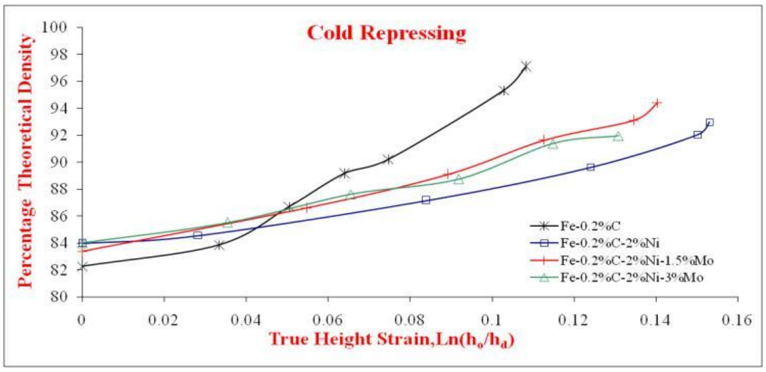


Fig. 7: Plots of Percentage Theoretical Density versus True Height Strain of Sintered and Cold Repressed Fe-C-Ni-Mo Alloy Preforms.

Correlation between axial Stress, true height strain and theoretical density of cold forged low alloy P/M steels:

Plastic deformation and densification characteristics of cold forged low alloy P/M steels are explained in section 3.1 to 3.3. The various results pertaining to the cold deformations of the various low alloy P/M steels, namely stress, strain and density are analysed using the Design of Experiments Software Design Expert 8, and these three parameters are correlated with each other using the response surface analysis. The corresponding correlations between stress, strain and density as obtained using the software is given in table 1 and 2.

Table 1: Correlation between axial stress, true height strain and theoretical density of sintered preforms subjected to cold upsetting– through response surface analysis.

S.No	Composition	Final Equation in terms of actual factors				R^2
1	Fe-0.2%C	σ_a = 8019	ε_a + 27 $\rho_{\% Theo}$ - 82 ε_a $\rho_{\% Theo}$ - 2180			0.9966
2	Fe-0.2%C-2%Ni	σ_a =12264	ε_a + 20 $\rho_{\% Theo}$- 132		ε_a $\rho_{\% Theo}$ –1490	0.9815
3	Fe-0.2%C-2%Ni-1.5%Mo	σ_a = 2271	ε_a+ 21	ρ% Theo-22 εa	$\rho_{\% Theo}$-1444	0.9967
4	Fe-0.2%C-2%Ni-3%Mo	σ_a = 2297	ε_a+19	ρ% Theo- 22 εa	$\rho_{\% Theo}$ -1316	0.9984

Table 2: Correlation between axial stress, true height strain and theoretical density of low alloy steel preforms subjected to cold repressing – through response surface analysis

S.No	Composition	Final Equation in terms of actual factors	R2	
1	Fe-0.2%C	σ_a = -7707+ 44693 ε_a + 94 $\rho_{\% Theo}$ - 472 ε_a $\rho_{\% Theo}$	0.9906	
2	Fe-0.2%C-2%Ni	σ_a = 13196 –71323 ε_a -156 $\rho_{\% Theo}$ + 939 ε_a $\rho_{\% Theo}$	0.9907	
3	Fe-0.2%C-2%Ni-1.5%Mo	σ_a = 8122 -53144 ε_a -95 $\rho_{\% Theo}$ +720 ε_a $\rho_{\% Theo}$	0.9895	
4	Fe-0.2%C-2%Ni-3%Mo	σ_a = 3534- 9639 ε_a -42 $\rho_{\% Theo}$ +231 ε_a $\rho_{\% Theo}$	0.9903	

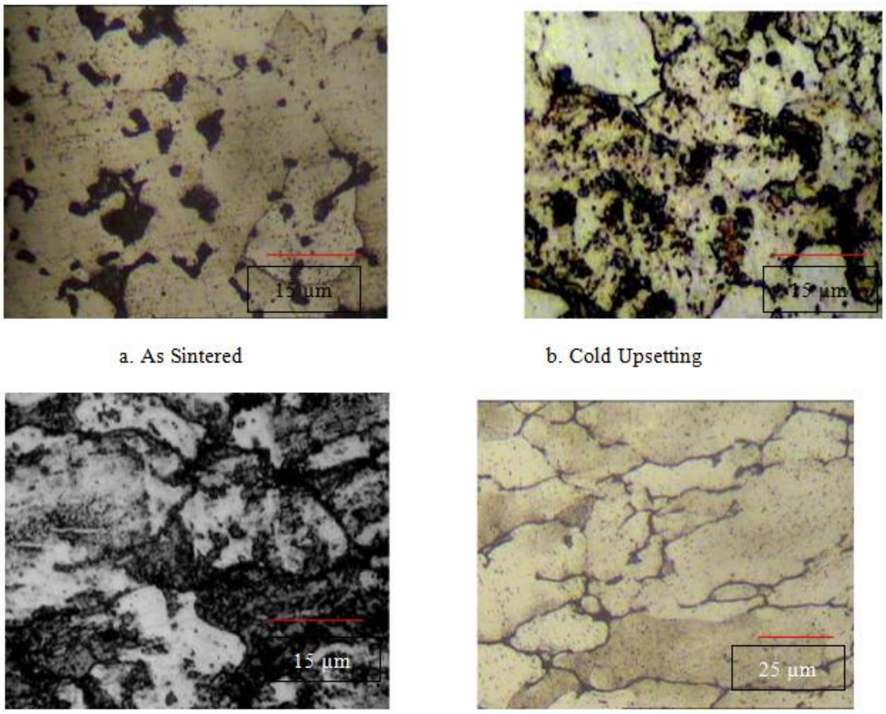
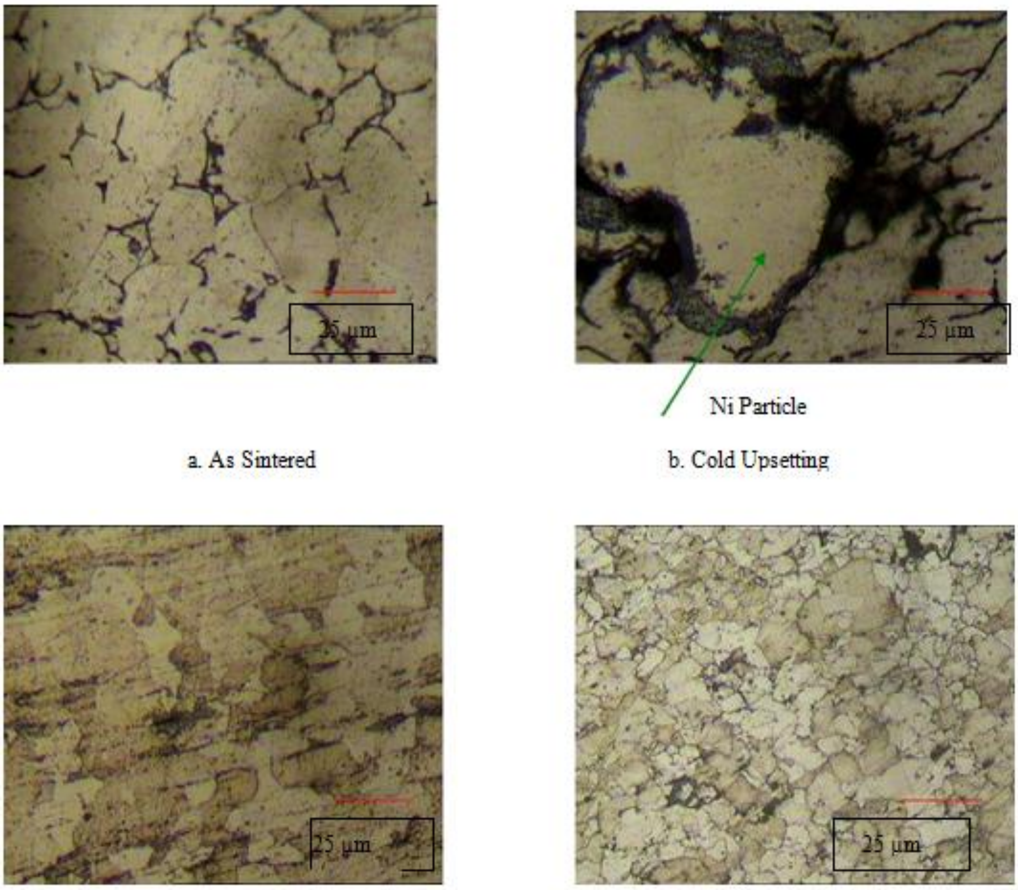


Fig. 8: Microstructures of Fe-0.2%C, 5% Nital.

Microstructure and Energy Dispersive X-ray analysis (EDX):

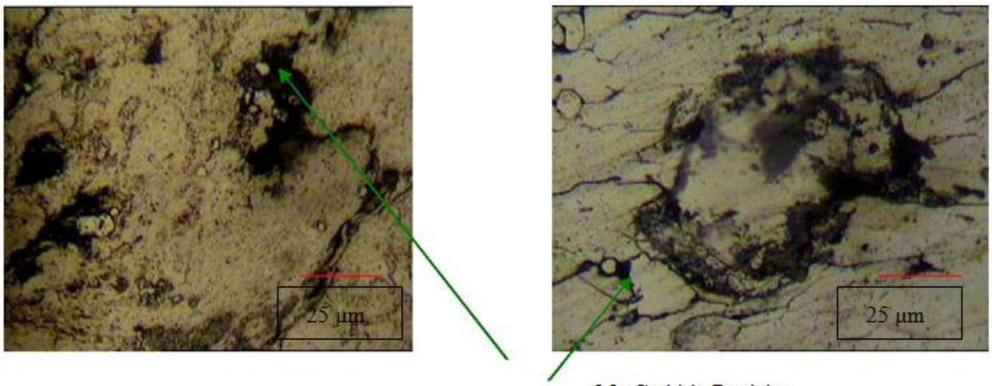
The microstructures of the as sintered, cold upset, hot upset and cold repressed Fe-0.2 % C P/M steels are displayed in fig.8. The microstructure is basically ferrite and pearlite. The microstructure of the hot deformed preforms has a uniform distribution of fine pearlites in a ferritic matrix. Fine and rounded pores are also observed both within the grains as well as across the grain boundaries. The as sintered microstructure of Fe-0.2%C steel shows a large number of pores, which are of larger size and irregular in shape. The larger sized pores get reduced in size and become rounded at the end of the post sintering forming processes. The cold repressed microstructure exhibits very few rounded pores along the grain boundaries. The microstructures of as sintered, cold upset, hot upset and cold repressed Fe-0.2 % C-2 % Ni steels are shown in the fig. 9. The structure is basically ferritic with numerous retained austenite grains present. The microstructure also exhibits uniform distribution of ferrite grains and austenite grains along with Ni particles distributed uniformly. The microstructures of as sintered preforms shows larger number of intergranular pores. It is also evident that cold repressing process has resulted in a microstructure of the steel with uniform, equiaxed grains of ferrite & austenite with well-defined boundaries. The microstructures of as sintered, cold upset, hot upset and cold repressed Fe-0.2 % C-2 % Ni-1.5% Mo steels are shown in the fig. 10. The structure indicates the presence of fine-grained ferrite with dark pearlite, bainite and a number of distributed Mo carbides and Ni particles. Fig. 11 illustrates the microstructures of the Fe-C-Ni-3%Mo alloy under as sintered, cold upset, hot upset and cold repressed steels. The structure is basically ferritic- pearlite and bainite with some retained austenite. The cold upset forged microstructure shows a few grains of fine austenite along with ferrite grains. The alloy preforms also have a ferritic structure with some massive Mo particulates distributed along the grain boundaries. Numerous round and elongated pores are also visible in the micrographs. Rounded pores of very fine size are located within the grains, whereas the larger size pores are found along the grain boundaries. The presence of un-dissolved carbides in the grain structure may be attributed to the addition of Ni. The EDX sum spectra shown in fig. 12 are the evident for the presence of Ni, Mo & C, which influence for the formation of its carbide phase.



a. As Sintered b. Cold Upsetting

c. Hot Upsetting d. Cold repressed

Fig. 9: Microstructures of Fe-0.2% C-2% Ni, 5% Nital.



a. As Sintered b. Cold Upsetting

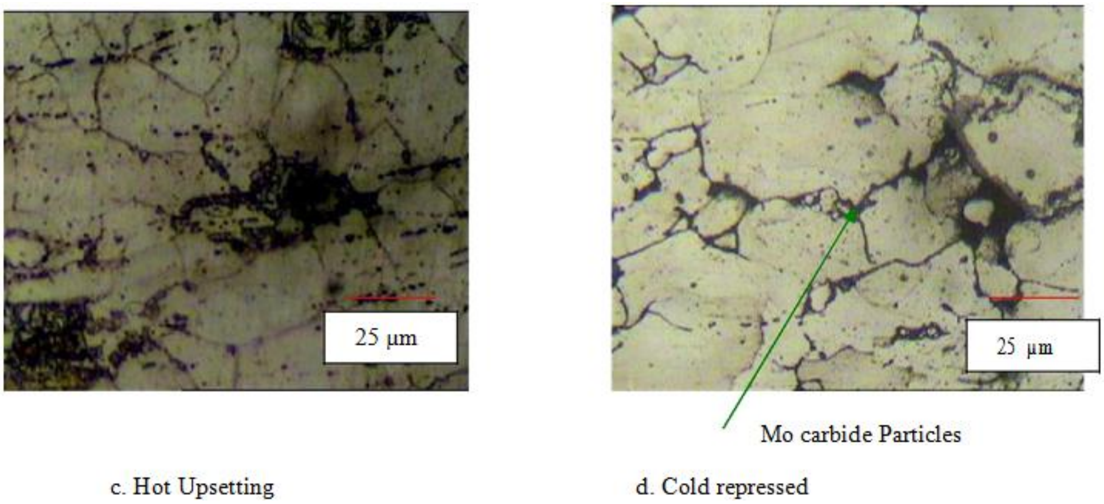


Fig. 10: Microstructures of Fe-0.2% C-2% Ni-1.5%Mo, 5% Nital.

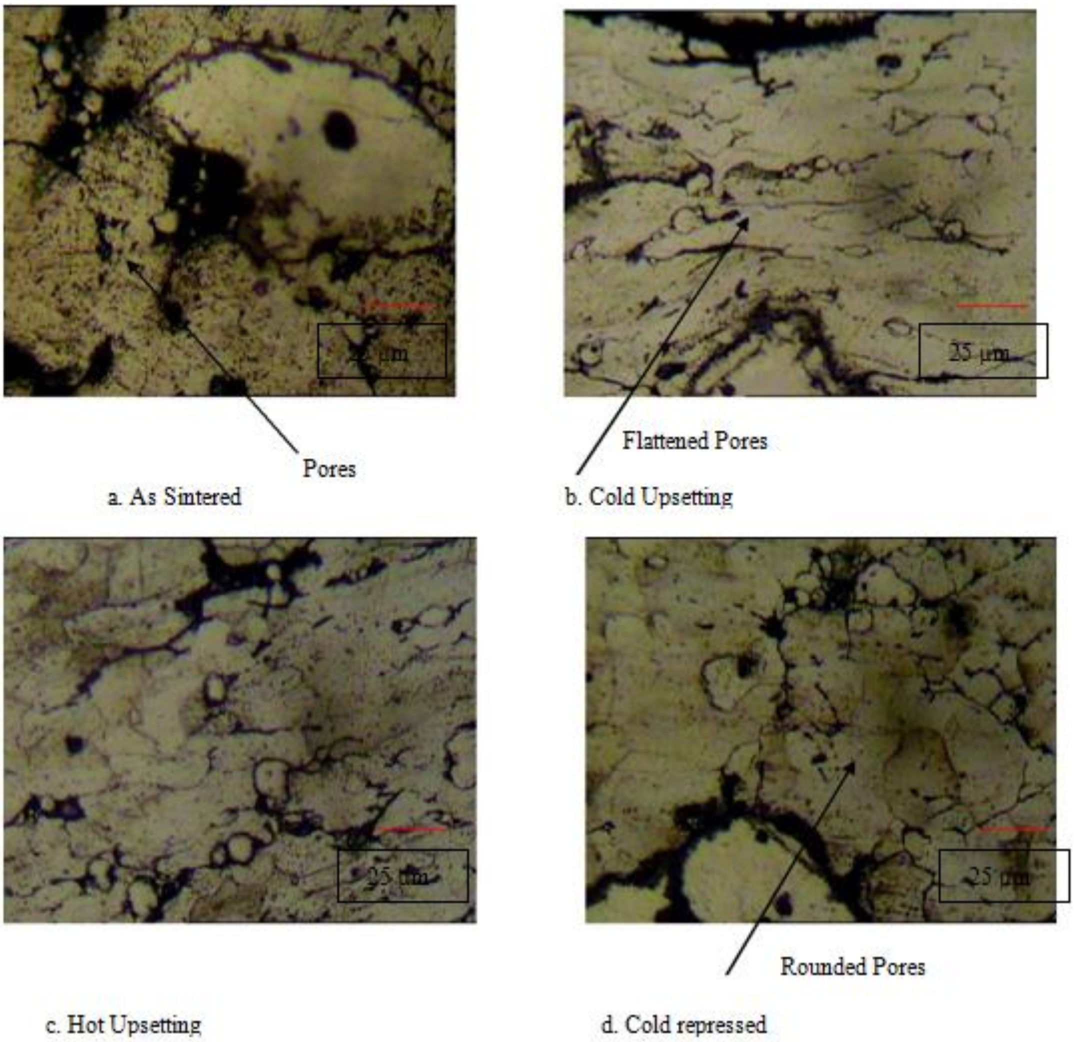
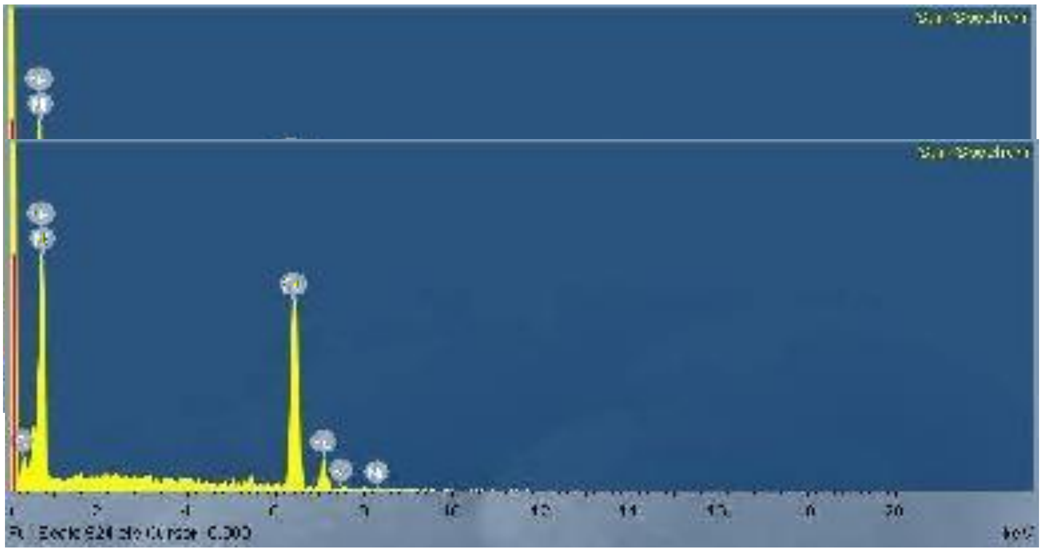
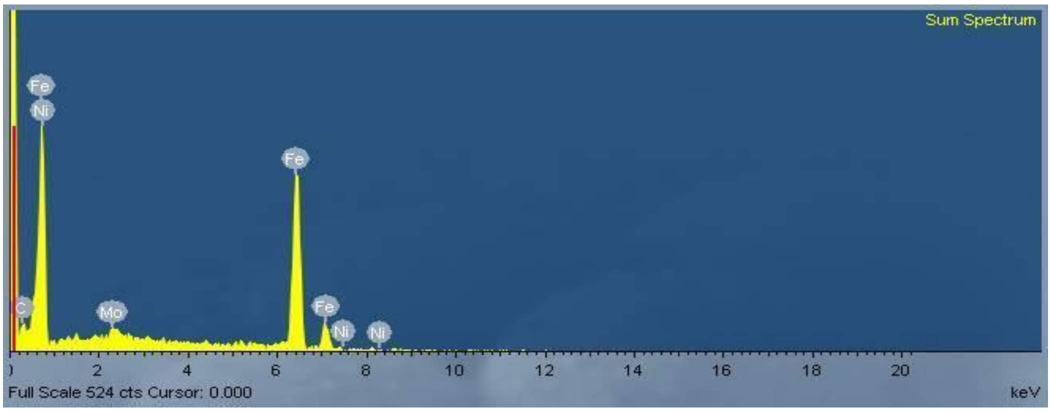


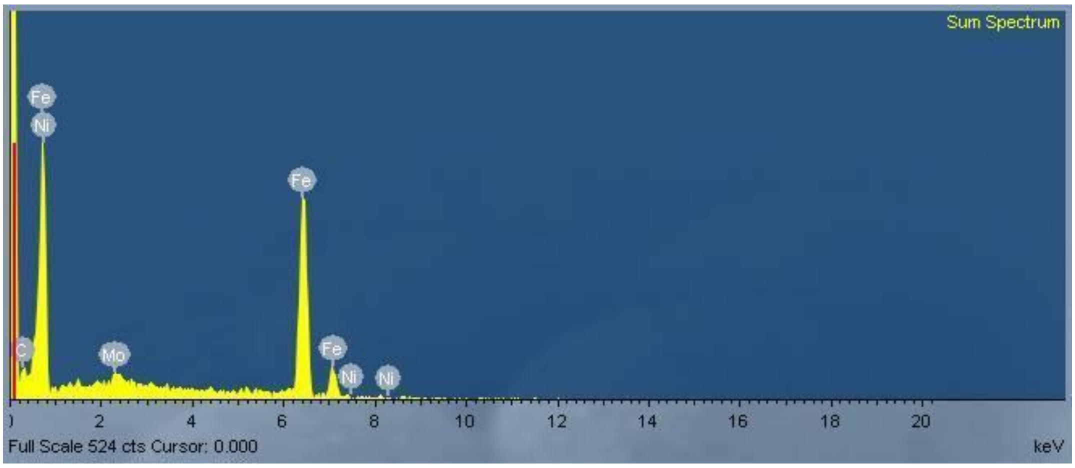
Fig. 11: Microstructures of Fe-0.2% C-2% Ni- 3%Mo, 5% Nital.



a



b



c

Fig. 12: Sum spectra of EDX report of *a) Fe-0.2%Ni b) Fe-0.2%C-2%Ni1.5%Mo c) Fe-0.2% C-2% Ni-3% Mo low alloy P/M steel*

Conclusions:

The plastic deformation and densification level of the sintered plain carbon steel is the highest under both hot and cold upsetting conditions. Addition of the alloying element Mo enhances the densification levels of Fe-C-Ni steel during cold and hot upset deformations. Nickel promotes austenitic grain structure in the forged alloys. Addition of Ni alone to plain carbon steel lowers the deformation as well as the percentage theoretical density during cold and hot forging. Incomplete densification of the alloy is indicated by the presence of numerous fine and rounded pores (both intergranular and trans-granular) in the microstructures. Hot upsetting of the preforms leads to deformations, which are much larger, compared to cold working. Densification of the alloy preforms during hot upsetting is higher than that during cold upsetting, but is larger than that during repressing. Microstructures of Ni-Mo alloyed steels are basically ferritic-austenitic-pearlitic with the presence of Mo carbides, Ni particles along grain boundaries. Cold repressing of the alloys has led to an equi-axed fine-grained microstructure.

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