CHAPTER 6: EXPERIMENTAL RESULTS AND DISCUSSION

6.1. Introduction

The plastic deformation, densification and formability of the sintered steels preforms containing Cr, Ni & Mo during three post-sintering operations namely, cold upsetting, cold repressing and hot upsetting are considered.

The experimentally determined parameters are: the axial stress, axial strain and percentage theoretical density. The calculated parameters are: hoop stress, hoop strain, radial stress, radial strain, effective stress, effective strain, mean stress, mean strain, Poison’s ratio, stress formability parameter and strain formability parameter.

The following plots are made in order to study and correlate the influence of various alloying elements.

1. Axial Stress vs. True Height Strain
2. Axial Stress vs. Percentage Theoretical Density
3. Percentage Theoretical Density vs. True Height Strain
4. Stress Formability Index vs. Strain Formability Index

The discussions on densification and plastic deformation of the alloys are primarily based on the considerations of the true axial stress and true axial strain alone. In reality, triaxial states of stress and strain exist during the forging process. Considering the triaxial state of stress and strain, the stress formability index and strain formability index are evaluated adopting the method available in the existing literature [54-58]. The formability index is
correlated with the fractional theoretical density for the cold upset, cold repressed and hot upset forged preforms of the various alloys to facilitate the study of the impact of density and alloying elements on formability of the new alloy compositions.

The stress formability index, as defined by Vujovic and Shabaik [54], is a non-dimensional index, and is a function of mean stress and effective stress. Similarly the strain formability index is a function of mean strain and effective strain. A lower stress and strain formability index values is an indication of poor formability behaviour and a higher index value indicates good formability of materials. The strain formability index is employed for specifying fracture limit of formability. The stress and strain formability parameters evaluated at the instance of material failure i.e., formation of fine 45° cracks on the bulged free surface, are considered for specifying the formability limit of materials. Influence of microstructures of the deformed alloys on deformation behaviour has also been correlated with the various workability parameters.

6.2. Plastic deformation and densification

6.2.1. Cold Upsetting

The experimental results of the cold upset forged preforms are shown in table 6.1.
Table 6.1. Experimental observations for cold upset, cold repressed and hot upset forged preforms

<table>
<thead>
<tr>
<th>Sl.No</th>
<th>Alloy Composition</th>
<th>Cold Upsetting</th>
<th>Cold Repressing</th>
<th>Hot Upsetting</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Axial stress, Mpa</td>
<td>True Height Strain</td>
<td>Percentage Theoretical Density</td>
</tr>
<tr>
<td>1</td>
<td>Fe-0.2%C</td>
<td>0.00 82.8 0.83 0.33 0.00 0.00 82.27 0.82 0.34 0.00 0.00 82.9 0.83 0.34 0.00</td>
<td>0.09 85.2 0.85 0.33 1.54 2.93 0.09 83.86 0.84 0.36 1.97 1.24 0.06 84.92 0.84 0.35 3.84</td>
<td>0.09 85.2 0.85 0.33 2.06 2.7 0.09 84.56 0.85 0.36 2.41 1.45 0.09 86.94 0.87 0.38 5.95</td>
</tr>
<tr>
<td>2</td>
<td>Fe-0.2%C-2%Ni</td>
<td>0.00 84.8 0.85 0.36 0.00 0.00 83.98 0.84 0.36 0.00 0.00 83.98 0.84 0.36 0.00</td>
<td>0.01 84.5 0.85 0.36 2.06 2.7 0.01 84.56 0.85 0.36 2.41 1.45 0.09 86.94 0.87 0.38 5.95</td>
<td>0.01 84.5 0.85 0.36 2.06 2.7 0.01 84.56 0.85 0.36 2.41 1.45 0.09 86.94 0.87 0.38 5.95</td>
</tr>
<tr>
<td>3</td>
<td>Fe-0.2%C-2%Ni-1.5%Mo</td>
<td>0.00 84.8 0.85 0.36 0.00 0.00 83.98 0.84 0.36 0.00 0.00 83.98 0.84 0.36 0.00</td>
<td>0.01 84.5 0.85 0.36 2.06 2.7 0.01 84.56 0.85 0.36 2.41 1.45 0.09 86.94 0.87 0.38 5.95</td>
<td>0.01 84.5 0.85 0.36 2.06 2.7 0.01 84.56 0.85 0.36 2.41 1.45 0.09 86.94 0.87 0.38 5.95</td>
</tr>
</tbody>
</table>

Table 6.1. Continued
<table>
<thead>
<tr>
<th></th>
<th>Fe-0.2%C-2%Ni-3%Mo</th>
<th>Fe-0.2%C-1%Cr</th>
<th>Fe-0.2%C-2%Cr</th>
<th>Fe-0.2%C-1%Cr-2%Ni</th>
<th>Fe-0.2%C-1%Cr-2%Ni-1.5%Mo</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>0  0  84.1  0.84 0.37  0  0  0  0  84.01  0.84 0.37  0  0  0  83.84 0.84 0.35  0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>317 0.03 85.1 0.85 0.37  2.16  3.58</td>
<td>487.1 0.4  90.8 0.9 0.41  407 0. 84 0.37 0 0 0  0 0 84 0.84 0.37 0</td>
<td>583.6 0.46 92.4 0.93 0.44  4.15  4.46</td>
<td>445 0.25 91 0.91 0.42  3.39  3.85</td>
<td>1751 0.15 92.7 0.93 0.43  3.89  4.16</td>
</tr>
<tr>
<td></td>
<td>325.5 0.04 85.51  0.86 0.37  2.57  1.461</td>
<td>302  0.12 87.4 0.87 0.39  2.54  3.41</td>
<td>508.9 0.5  89.7 0.9 0.41  3.08  3.86</td>
<td>518 0.36 91.4 0.92 0.43  3.76  3.93</td>
<td></td>
</tr>
<tr>
<td></td>
<td>539.8 0.07 87.61  0.88 0.39  2.99  1.467</td>
<td>503.5 0.31 88.9 0.89 0.4  2.84  3.77</td>
<td>435.4 0.03 85.04  0.85 0.37  2.14  1.429</td>
<td>583.6 0.46 92.4 0.93 0.44  4.15  4.46</td>
<td></td>
</tr>
<tr>
<td></td>
<td>745.8 0.09 88.74  0.89 0.4  3.24  1.47</td>
<td>960.5 0.11 91.37 0.91 0.42  3.98  1.477</td>
<td>666.8 0.57 93.4 0.93 0.44  4.15  4.46</td>
<td>666.8 0.57 93.4 0.93 0.44  4.15  4.46</td>
<td></td>
</tr>
<tr>
<td></td>
<td>917.15 0.13 91.94 0.92 0.43  4.17  1.479</td>
<td>80.39 89.34 0.9 0.4  8.02</td>
<td>1372 0.07 95.77 0.96 0.46  5.47  1.479</td>
<td>1372 0.07 95.77 0.96 0.46  5.47  1.479</td>
<td></td>
</tr>
<tr>
<td></td>
<td>85.1 0.85 0.37  2.16  3.58</td>
<td>317 0.03 85.1 0.85 0.37  2.16  3.58</td>
<td>542.8 0.4 90.3 0.9 0.41  3.16  4.92</td>
<td>583.6 0.46 92.4 0.93 0.44  4.15  4.46</td>
<td></td>
</tr>
<tr>
<td></td>
<td>85.08 84.01 0.84 0.37  0  0  0  0  83.84  0.84 0.35  0  0  0  83.84 0.84 0.35  0</td>
<td>85.1 0.85 0.37  2.16  3.58</td>
<td>586.7 0.47 91.5 0.91 0.42  3.49  4.24</td>
<td>586.7 0.47 91.5 0.91 0.42  3.49  4.24</td>
<td></td>
</tr>
<tr>
<td></td>
<td>85.08 84.01 0.84 0.37  0  0  0  0  83.84  0.84 0.35  0  0  0  83.84 0.84 0.35  0</td>
<td>85.1 0.85 0.37  2.16  3.58</td>
<td>637.6 0.6 91.8 0.92 0.42  3.59  4.4</td>
<td>637.6 0.6 91.8 0.92 0.42  3.59  4.4</td>
<td></td>
</tr>
</tbody>
</table>
6.2.1.1. Axial Stress vs. True Height Strain

The plastic deformation behaviour of the alloy preforms is predicted from the plots between axial stress and true axial strain. Figure 6.1 shows the plots representing the stress applied during cold upsetting under various levels of true height strain of the cylindrical preforms of aspect ratio (A.R.) 0.5 for the Fe-C-Ni-Mo low alloy P/M steels for the three different alloy compositions of Ni and Mo and plain carbon (0.2%C) P/M steel. 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.

Figure 6.2 depicts the plots of Fe-C-Cr-Ni-Mo low alloy P/M steels for four different alloy compositions of Cr, Ni and Mo as alloying elements. These two graphs (Figures 6.1 & 6.2) emphasize the influence of various alloying elements on stress-strain behaviour of Fe-0.2%C steels. It is clearly evident from the Figure 6.2, that about 25% enhanced plastic deformation is observed due to the addition of Cr to Ni-Mo steel. However, the
flow stress required for the given plastic deformation level is 17% more in these alloys compared to Ni-Mo steel. It is also evident from the Figure 6.2 that the addition of 2% Cr alone to plain carbon steel lowers the plastic deformation level. This is an indication of this alloy’s reduced tendency for plastic deformation among the alloys. Further, addition of the alloying element Mo enhances the plastic deformation. An alloy containing 2% Cr and 1% Cr shows similar behaviour of axial strain with respect to the applied stress. In general, the plain carbon steel with 0.2% C shows the highest level of axial strain of 0.75 and therefore, has the tendency to undergo larger plastic deformation. It is therefore observed that the addition of either 1% Cr or 2% Cr to the base material, namely, Fe-0.2% C, does not contribute much towards the increase in deformation levels. It is also concluded that the alloying element Cr alone when added to plain carbon steel has an influence of reducing its plastic deformation. However, in combination with Ni & Mo, Cr improves the plastic deformation behaviour. The required flow stress values for this alloy are greater due to the hard Cr carbides precipitated in a soft ferrite-pearlite microstructure. The Energy Dispersive X ray Analysis (EDX) sum spectra of the steels are shown in Figures 6.3.

From the Figures 6.1 & 6.2, it is also observed that, during the cold upsetting, the mode of deformation of the preforms follows two distinctly different stages. There is a steep increase in applied stress during the initial stages of compression with very low axial deformations. This may be attributed to the rapid shrinkage of pores leading to the hardening of the matrix material, called geometric hardening. During the second stage of deformation there is almost a linear increase in deformation with respect to applied stress.
The second stage is characterized by a steep increase in deformation without much increase in flow stress.

Figure 6.1  Plots of axial stress vs. true height strain of sintered and cold upset forged Fe-C-Ni-Mo low alloy steel preforms.

Figure 6.2  Plots of axial stress vs. true height strain of sintered and cold upset forged Fe-C-Cr-Ni-Mo low alloy steel preforms.

It was observed [42] that, the relationship between axial flow stress and true height strain for the preforms must follow a power law expression of the form:

\[ \sigma = K \varepsilon^n \]  \hspace{1cm} 6.1

Where, ‘\( \sigma \)’ is axial stress, ‘\( \varepsilon \)’ 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 and the same are shown in Table 6.2. From the tables it is observed that the $R^2$ values 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.

Among the alloys considered the work hardening exponent ‘$n$’ is higher for Cr, Cr-Ni and Cr-Ni-Mo steels compared to Ni and Ni-Mo steels. Therefore, it is contended that addition of the alloying element Cr leads to tendency of the alloy to get work hardened during cold upsetting process. Further, it is also observed that the stress constant ‘$K$’ is also higher for these alloys. Hence, addition of alloying element Cr helps the alloy withstand high axial stress before the appearance of surface cracks.

Table 6.2. Power law equation and $R^2$ values of low alloy P/M steels.

<table>
<thead>
<tr>
<th>Sl.No</th>
<th>Alloy Composition</th>
<th>Power Law Equation-Cold Upsetting</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fe-0.2%C</td>
<td>$\sigma_a = 655 \varepsilon_a^{0.5205}$</td>
<td>0.9812</td>
</tr>
<tr>
<td>2</td>
<td>Fe-0.2%C-2%Ni</td>
<td>$\sigma_a = 614 \varepsilon_a^{0.228}$</td>
<td>0.998</td>
</tr>
<tr>
<td>3</td>
<td>Fe-0.2%C-2%Ni-1.5%Mo</td>
<td>$\sigma_a = 649 \varepsilon_a^{0.236}$</td>
<td>0.989</td>
</tr>
<tr>
<td>4</td>
<td>Fe-0.2%C-2%Ni-3%Mo</td>
<td>$\sigma_a = 688 \varepsilon_a^{0.240}$</td>
<td>0.981</td>
</tr>
<tr>
<td>5</td>
<td>Fe-0.2%C-1%Cr</td>
<td>$\sigma_a = 710 \varepsilon_a^{0.4273}$</td>
<td>0.9834</td>
</tr>
<tr>
<td>6</td>
<td>Fe-0.2%C-2%Cr</td>
<td>$\sigma_a = 678 \varepsilon_a^{0.4169}$</td>
<td>0.9976</td>
</tr>
<tr>
<td>7</td>
<td>Fe-0.2%C-1%Cr-2%Ni</td>
<td>$\sigma_a = 852 \varepsilon_a^{0.4129}$</td>
<td>0.9705</td>
</tr>
<tr>
<td>8</td>
<td>Fe-0.2%C-1%Cr-2%Ni-1.5%Mo</td>
<td>$\sigma_a = 865 \varepsilon_a^{0.4914}$</td>
<td>0.996</td>
</tr>
</tbody>
</table>
6.2.1.2. Axial Stress vs. Percentage Theoretical Density

The densification behaviour of the alloy preforms with respect to flow stress required during cold upsetting is understood from the plots of percentage theoretical density versus axial stress, which are shown in Figures 6.3 & 6.4.

It is observed from the densification curves shown in Figure 6.3 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° with respect to axial direction. Further, addition of Mo to Fe-C-2% Ni enhances the densification rate thereby acting contradictory to Ni. 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 carbide particles along the grains and grain boundaries appear to promote the ability of the Mo alloyed steel to withstand up to 490 kN.

From Figure 6.4, we observe that the highest density attained in the case of 1% Cr-2% Ni-1.5% Mo and 1% Cr-2% Ni alloy preforms is about 98%. Adding Ni and Cr to the base composition has resulted in the highest density but only under the application of the highest axial stress value of 745MPa. The densification process of the cold upset plain carbon steel preforms is found to follow three distinctly different stages during cold upsetting. These stages are identified in the plots of applied stress versus percentage theoretical density of the preforms. During the first stage, a rapid increase in axial applied stress is observed with lower rate of increase in densification because of the effect of geometric hardening. During the second stage, a uniform rate of densification with respect to the applied stress can be observed. Subsequently, during the last phase of densification, there is a rapid increase of applied stress, with a correspondingly slow rate of densification. Unlike the preforms of Fe-0.2% C, the preforms with the addition of Cr, Cr-Ni and Cr-Ni-Mo, are observed to undergo a uniform rate of densification right from the beginning of densification. During the end stage, a rapid increase in density with lower rates of axial applied stress values is observed. To sum up, the alloying element Cr along with Ni & Mo is observed to improve the densification behaviour. However, the flow stress required for the given densification level is higher for these alloys. It is
concluded that the alloying element Cr alone, when added to plain carbon steel, has an influence of reducing the densification due to the formation of hard Cr carbide particles along the grains and grain boundaries. However, Cr in combination with Ni and Ni-Mo enhances the densification. The required flow stress values for Fe-C-Cr-Ni-Mo steels are greater due to the hard Cr and Mo carbides precipitated in a ferrite-pearlitic microstructure.

Figure 6.3. Plots of axial stress vs. percentage theoretical density of sintered and cold upset forged Fe-C-Ni-Mo low alloy steel preforms

Figure 6.4. Plots of axial stress vs. percentage theoretical density of sintered and cold upset forged Fe-C-Cr-Ni-Mo low alloy steel preforms.
6.2.1.3. Percentage Theoretical Density vs. True Height Strain

Figures 6.5 & 6.6 depict the plots representing the plastic deformation and densification behaviour of Fe-C-Ni-Mo and Fe-C-Cr-Ni-Mo low alloy P/M steels undertaken for the present research respectively.

Figure 6.5. Plots of percentage theoretical density vs. true height strain of sintered and cold upset forged Fe-C-Ni-Mo low alloy steel preforms.

Figure 6.6. Plots of percentage theoretical density vs. true height strain of sintered and cold upset forged Fe-C-Cr Ni-Mo low alloy steel preforms.
The densification versus deformation plots of the cold upset preforms, shown in Figure 6.5 for the Fe-C-Ni-Mo alloys, indicate that the plain carbon steel preforms exhibit the highest deformation as well as densification compared to the other alloy preforms. Addition of 2% Ni to plain carbon steel leads to a marginal reduction in densification and deformation, about 30%, in comparison with plain carbon steel. It is explained [16] that the addition of Ni stabilizes the austenite phase of iron during sintering, and this leads to formation of a soft austenitic phase in a very soft ferrite-pearlite microstructure. During cold upsetting, it is observed that even at lower applied load fine cracks on the bulged circumference were noticed. Hence, the extent of plastic deformation and densification is observed to be very low in this alloy compared to plain carbon steel and Fe-C-Ni-Mo steels. Addition of either 1.5 % or 3% Mo to Fe-0.2% C-2% Ni shows similar trend in plastic deformation and densification. Due to the addition of Mo, a maximum of 2% increase in percentage theoretical density is observed. Similarly the addition of 1.5% Mo to Fe-0.2% C-2% Ni leads to enhancement of the plastic deformation by about 5% compared to Fe-C-Ni steels and about 15% increase in plastic deformation due to the addition of 3% Mo to Fe-C-Ni steels is also observed.

From the above, it is concluded that addition of either 1.5% Mo or 3% Mo enhances both plastic deformation and densification. The formation of Mo carbides in a ferrite-pearlite structure helps to withstand higher stress during cold upsetting. In a summary, a soft ferrite-pearlite matrix of the Mo alloyed steel is responsible for the enhanced deformation levels.
The influence of Cr addition to the base composition Fe-C-Ni-Mo on the plastic deformation and densification of the steel is shown in Figure 6.6. From the plots it is observed that at maximum applied load conditions, the plastic deformations of all the alloys under investigations show almost same due to the addition of alloying element Cr. There is considerable difference in percentage theoretical density at maximum applied load levels.

From the plots it is observed that for a true height strain of 0.65, the plain carbon steel and Fe-0.2% C-1% Cr-2% Ni-1.5% Mo steel show the same percentage theoretical density (93.5%). There is no significant variation in densification is noticed due to the addition of 1% Cr. Addition of more 2% Cr to plain carbon steel, about 3% reduction in percentage theoretical density compared to plain carbon steel. This is due to the formation of more distributed Cr carbide particles along the grains and transgranular grain boundaries. This makes the preforms more brittle and restricts the pore closure, which leads to lowering of the densification. Addition of the alloying element Ni and Mo to Fe-0.2% C-1% Cr steel influence to form soft austenite phase with hard Cr & Mo carbide particles on soft ferrite pearlite matrix. This helps us the alloy withstand higher axial stresses during cold upsetting, and a corresponding 4% increase in percentage theoretical density compared to Fe-0.2% C-2% Cr steel.

In conclusion, the plain carbon steel preforms experience the highest plastic deformation levels of about 0.76 among the Fe-C-Ni-Mo steels. The deformation of the alloy steel is reduced by about 40% due to the addition of Ni alone to plain carbon steel. The addition of the alloying element Mo to Fe-C-Ni leads to 15% higher plastic deformation. Addition
of higher Cr with plain carbon steel tends to reduce the plastic deformation by about 10%.

6.2.1.4. Fracture Limit Analysis

The limiting condition of stress-strain under which fine surface cracks begin to appear on the bulged free surface of the preforms has been considered as the fracture limit.

The nature of the fracture curve shown in Figure 6.7 is drooping type, which indicates that at lower strain levels, the material can withstand higher level of stress without fracture and vice-versa.

![Fracture Limit Analysis](image)

Figure 6.7. Fracture limit plot of Fe-Cr-Ni-Mo low alloy cold upset forged P/M steels.
6.2.1.5. Correlation between Axial Stress, True Height Strain and Theoretical Density of Cold Upset Forged Low Alloy P/M Steels.

Plastic deformation and densification characteristics of cold upset forged low alloy P/M steels are explained in section 6.2.1.1. to 6.2.1.3. 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 6.3.

Table 6.3. Correlation between axial stress, true height strain and theoretical density of sintered preforms subjected to cold upsetting—through response surface analysis

<table>
<thead>
<tr>
<th>S.No</th>
<th>Composition</th>
<th>Final Equation in terms of actual factors</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fe-0.2%C</td>
<td>( \sigma_a = 8019 \ v_a + 27 \ \rho_{% \text{ Theo}} - 82 \ v_a \ \rho_{% \text{ Theo}} - 2180 )</td>
<td>0.9966</td>
</tr>
<tr>
<td>2</td>
<td>Fe-0.2%C-2%Ni</td>
<td>( \sigma_a = 12264 \ v_a + 20 \ \rho_{% \text{ Theo}} - 132 \ v_a \ \rho_{% \text{ Theo}} - 1490 )</td>
<td>0.9815</td>
</tr>
<tr>
<td>3</td>
<td>Fe-0.2%C-2%Ni-1.5%Mo</td>
<td>( \sigma_a = 2271 \ v_a + 21 \ \rho_{% \text{ Theo}} - 22 \ v_a \ \rho_{% \text{ Theo}} - 1444 )</td>
<td>0.9967</td>
</tr>
<tr>
<td>4</td>
<td>Fe-0.2%C-2%Ni-3%Mo</td>
<td>( \sigma_a = 2297 \ v_a + 19 \ \rho_{% \text{ Theo}} - 22 \ v_a \ \rho_{% \text{ Theo}} - 1316 )</td>
<td>0.9984</td>
</tr>
<tr>
<td>5</td>
<td>Fe-0.2%C-1%Cr</td>
<td>( \sigma_a = 5147 + 341 \ v_a - 55 \ \rho_{% \text{ Theo}} + 6 \ v_a \ \rho_{% \text{ Theo}} - 3261 )</td>
<td>0.9736</td>
</tr>
<tr>
<td>6</td>
<td>Fe-0.2%C-2%Cr</td>
<td>( \sigma_a = 5002 \ v_a + 52 \ \rho_{% \text{ Theo}} - 57 \ v_a \ \rho_{% \text{ Theo}} - 3261 )</td>
<td>0.9980</td>
</tr>
<tr>
<td>7</td>
<td>Fe-0.2%Cr-1%Cr-2%Ni</td>
<td>( \sigma_a = 5523-5214 \ v_a - 57 \ \rho_{% \text{ Theo}} + 65 \ v_a \ \rho_{% \text{ Theo}} + 3261 )</td>
<td>0.9989</td>
</tr>
<tr>
<td>8</td>
<td>Fe-0.2%C-1%Cr-2%Ni-1.5%Mo</td>
<td>( \sigma_a = 3435 \ v_a + 21 \ \rho_{% \text{ Theo}} - 31 \ v_a \ \rho_{% \text{ Theo}} - 1620 )</td>
<td>0.9981</td>
</tr>
</tbody>
</table>
6.2.2. Cold Repressing

Repressing is a mode of deformation in which no lateral flow of material is permitted. In repressing the axial plastic deformation levels are much lower due to the lateral constraint. The experimentally determined values of the axial stress, true height strain and percentage theoretical density for the cold repressed preforms are shown in table 6.1.

6.2.2.1. Axial Stress vs. True Height Strain

The plastic deformation behaviour of cold repressed preforms of Fe-C-Ni-Mo and Fe-C-Cr-Ni-Mo are represented in plots of axial stress versus true height strain, as shown in Figures 6.8 and 6.9.
From the plots, it is observed that, the axial stress-strain behaviour for all the alloys is 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 repressing, a constant rate of increase in true axial strain is observed. Pores however have a tendency to get deformed sluggishly during repressing because pore flattening becomes rather difficult. 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 later stage of deformation due to the presence of finer pores in the preforms, which are very difficult to flatten or eliminate. The influence of alloying elements on flow stress and plastic deformation during cold repressing is similar to that observed for cold upsetting. Addition of Cr alone to plain carbon steel has led to lowers the plastic deformation and addition of both alloying elements Ni and Mo to Fe-C-1% Cr steel influence to enhance the plastic deformation.

Figure 6.9. Plots of axial stress vs. true height strain of sintered and cold repressed Fe-C-Cr-Ni-Mo low alloy steel preforms.
From the plots (Figures 6.8 & 6.9), it is inferred that, axial flow stress compared to the plain carbon steel, addition of 2% Ni has promoted 45% higher axial strain during cold repressing. Similarly 25% higher axial strain is observed for Fe-C-Ni-1.5% Mo and further by about 15% more axial height strain is noticed for Fe-C-Ni-3% Mo steels. There is no significant change in axial strain noticed due to the addition of 1% Cr. Addition of 2% Cr influence to lowers the axial deformation by about 40% for the same level of axial flow stress, compared to plain carbon steel. Correspondingly, the peak strain values in repressing are significantly lower than cold repressing. This is particularly because of the lateral constraint on flow. Similarly, the stresses required for a given axial strain are almost doubled compared to that of cold upsetting.

6.2.2.2. Stress vs. Percentage Theoretical Density

Referring to Figures 6.10 and 6.11, 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. Addition of all alloying elements Cr, Ni and Mo to plain carbon steel leads to 4.5% reduction in densification under cold repressing. 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.
Figure 6.10. Plots of axial stress vs. percentage theoretical density of sintered and cold repressed Fe-C-Ni-Mo low alloy steel preforms.

Figure 6.11. Plots of axial stress vs. percentage theoretical density of sintered and cold repressed Fe-C-Cr-Ni-Mo low alloy steel preforms.

6.2.2.3. Percentage Theoretical Density vs. True Height Strain

From the plastic deformation and densification behaviour plots shown in Figures 6.12 and 6.13, 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.
Addition of 2% Cr lowers the axial deformation by about 40% compared to the plain carbon steel without any remarkable change in the densification.

Figure 6.12. Plots of percentage theoretical density vs. true height strain of sintered and cold repressed Fe-C-Ni-Mo low alloy steel preforms.

Figure 6.13. Plots of percentage theoretical density vs. true height strain of sintered and cold repressed Fe-C-Cr-Ni-Mo low alloy steel preforms.
6.2.2.4. Correlation between Axial Stress, True Height Strain and Theoretical Density of Cold Repressed Low Alloy P/M Steels.

Plastic deformation and densification characteristics of cold repressed low alloy P/M steels are explained in section 6.2.2.1. to 62.2.3. The various results pertaining to the cold repressed preforms 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 6.4.
Table 6.4. Correlation between axial stress, true height strain and theoretical density of low alloy steel preforms subjected to cold repressing – through response surface analysis

<table>
<thead>
<tr>
<th>S.No</th>
<th>Composition</th>
<th>Final Equation in terms of actual factors</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fe-0.2%C</td>
<td>(\sigma_a = -7707 + 44693\ \varepsilon_a + 94\ \rho_{% Theo} - 472\ \varepsilon_a\ \rho_{% Theo})</td>
<td>0.9906</td>
</tr>
<tr>
<td>2</td>
<td>Fe-0.2%C-2%Ni</td>
<td>(\sigma_a = 13196 - 71323\ \varepsilon_a - 156\ \rho_{% Theo} + 939\ \varepsilon_a\ \rho_{% Theo})</td>
<td>0.9907</td>
</tr>
<tr>
<td>3</td>
<td>Fe-0.2%C-2%Ni-1.5%Mo</td>
<td>(\sigma_a = 8122 - 53144\ \varepsilon_a - 95\ \rho_{% Theo} + 720\ \varepsilon_a\ \rho_{% Theo})</td>
<td>0.9895</td>
</tr>
<tr>
<td>4</td>
<td>Fe-0.2%C-2%Ni-3%Mo</td>
<td>(\sigma_a = 3534 - 9639\ \varepsilon_a - 42\ \rho_{% Theo} + 231\ \varepsilon_a\ \rho_{% Theo})</td>
<td>0.9903</td>
</tr>
<tr>
<td>5</td>
<td>Fe-0.2%C-1%Cr</td>
<td>(\sigma_a = -5796 + 39475\ \varepsilon_a + 70\ \rho_{% Theo} - 391\ \varepsilon_a\ \rho_{% Theo})</td>
<td>0.9838</td>
</tr>
<tr>
<td>6</td>
<td>Fe-0.2%C-2%Cr</td>
<td>(\sigma_a = -9719 - 117951\ \varepsilon_a + 125\ \rho_{% Theo} + 1079\ \varepsilon_a\ \rho_{% Theo})</td>
<td>0.9891</td>
</tr>
<tr>
<td>7</td>
<td>Fe-0.2%Cr-1%Cr-2%Ni</td>
<td>(\sigma_a = -10922 - 29223\ \varepsilon_a + 138\ \rho_{% Theo} + 271\ \varepsilon_a\ \rho_{% Theo})</td>
<td>0.9922</td>
</tr>
<tr>
<td>8</td>
<td>Fe-0.2%C-1%Cr-2%Ni-1.5%Mo</td>
<td>(\sigma_a = -2466 - 27917\ \varepsilon_a + 32\ \rho_{% Theo} + 385\ \varepsilon_a\ \rho_{% Theo})</td>
<td>0.9983</td>
</tr>
</tbody>
</table>
6.3. Hot Upsetting

The calculated values of the deformation and densification parameters for the hot upset preforms are tabulated in table 6.1.

6.3.1. Plastic Deformation and Densification of Hot Upset Forged Preforms

The plastic deformation and densification response of the hot upset forged preforms of the low alloy P/M steels under investigation are illustrated in Figures 6.14. & 6.15. From these plots, it is observed that there is a linear relationship between plastic deformation and densification, irrespective of the alloy composition. The plain carbon P/M steel shows the highest level of plastic deformation and densification. Addition of the alloying elements, Ni and Mo has the influence of lowering the densification and plastic deformation rates. There is about 25% reduction in plastic deformation due to the presence of the alloying element Cr in the steel composition. There is no significant variation in densification observed among the alloy steels considered. The alloying elements Cr, Ni & Mo influence to reduce the extent of densification by about 7% compared to the plain carbon steel during hot upset forging. The presence of Cr and Mo carbide particulates and their influence on the plastic flow of the alloy steels may have led to lowering of the extent of plastic deformation in these steels.

In summary, addition of alloying elements such as Cr, Ni and Mo has a reducing effect on both plastic deformation and densification. The microstructures of the hot upset forged alloys are very similar to that of the cold forged alloys. Basically, the microstructures of
the alloys have ferritic-pearlitic base along with the carbide phase. Further, Ni alloyed steels have retained austenite phase, additionally.

Figure 6.14. Plots of percentage theoretical density vs. true height strain of sintered and hot upset forged Fe-C-Ni-Mo low alloy steel preforms.

Figure 6.15. Plots of percentage theoretical density vs. true height strain of sintered and hot upset forged Fe-C-Cr-Ni-Mo low alloy steel preforms.
6.4. Comparison of Limiting Plastic Deformations for Cold and Hot Forging

The bar chart shown in Figure 6.16 represents the maximum level of plastic deformation attained at the point of limiting axial stress for the alloy steels subjected to cold upsetting and hot upsetting processes.

![Bar chart showing limiting plastic deformation for cold and hot upsetting processes](image)

Figure 6.16. Comparison of limiting plastic deformation during various forging tests

The Fe-C-Ni-Mo steel is found to undergo 50% lower deformation during cold upsetting compared to hot upsetting. The corresponding difference in deformation levels is about 10% in case of the Cr steels.

6.5. Comparison of Limiting Densification for Cold and Hot Forging

Figure 6.17 compares the highest density attained during the cold & hot deformation processes for the various alloys. From the bar chat it is concluded that better densification response is observed during cold repressing of all the alloys except for Fe-0.2% C-1%
Cr-2% Ni steel and Fe-0.2% C-1% Cr-2% Ni-1.5% Mo steel. This may be due to the formation of carbides of the alloying elements Cr & Mo, which restricts the flow of material in axial direction by absorbing all applied axial stress instead of paving way for pore closure. This is also due to the lateral constraint by the die wall, which restricts the material flow in lateral direction.

Figure 6.17. Comparison of limiting densification during various forging tests

6.6. Microstructure of as-sintered, cold forged and hot forged preforms

The microstructures of the as sintered, cold upset, cold repressed and hot upsetting preforms of all the alloys under investigations are shown in Figures 6.18 to 6.25.

Table 6.5 summarizes of the important observations on the various photomicrographs.
Table 6.5. Observations of various photomicrographs of the deformed alloys

<table>
<thead>
<tr>
<th>Figure No</th>
<th>Alloy composition</th>
<th>As Sintered preforms</th>
<th>Cold upset forged preforms</th>
<th>Cold Repressed preforms</th>
<th>Hot Upset forged preforms</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.18</td>
<td>Fe-0.2%C</td>
<td>Ferrite-Pearlite</td>
<td>Fine pearlite in ferrite matrix</td>
<td>Ferrite- Pearlite, very clear fine grains and the grains boundaries</td>
<td>Uniform distribution of fine pearlites in a ferritic matrix, with fine rounded pores both within the grains as well as across the grain boundaries.</td>
</tr>
<tr>
<td>6.19</td>
<td>Fe-0.2%C-2%Ni</td>
<td>Ferritic and few fine pearlites, with lots of fine pores</td>
<td>Ferrite, some Ni particles, Austenite Phase</td>
<td>Very fine-grained structure, More distributed austenite grains with Ni particles.</td>
<td>Ferrite matrix, Distributed austenite grains, Limited pearlite traces, with least amount of pores</td>
</tr>
<tr>
<td>6.20</td>
<td>Fe-0.2%C-2%Ni-1.5%Mo</td>
<td>Distributed Ni particles &amp; distributed Mo carbide particulates with lots of pores</td>
<td>Rounded and flattened pores, ferrite with Mo carbide particulates both in granular and trans granular surfaces with a few dark pearlites. Stabilized austenite grains are also visible.</td>
<td>Rounded and flattened pores, ferrite with Ni, Mo carbide particulates both in granular and trans granular surfaces with a few dark pearlites. Stabilized austenite grains are also visible.</td>
<td>Ferrite grains, distributed Mo carbide with dark pearlite and bainite</td>
</tr>
<tr>
<td>6.21</td>
<td>Fe-0.2%C-2%Ni-3%Mo</td>
<td>Distributed Ni particles &amp; distributed Mo carbide particulates with lots of pores</td>
<td>Few grains of fine austenite along with ferrite grains with some massive unresolved carbide particles, rounded pores distributed along the grain boundaries.</td>
<td>Rounded and flattened pores, ferrite with Ni, Mo carbide particulates both in granular and transgranular surfaces with a few dark pearlites. Stabilized austenite grains are also visible.</td>
<td>Ferrite grains, distributed Mo carbide with dark pearlite and bainite</td>
</tr>
<tr>
<td>6.22</td>
<td>Fe-0.2 % C-1 % Cr</td>
<td>Basically ferritic with pores</td>
<td>Basically ferritic with tiny Cr carbides</td>
<td>Basically ferritic with tiny Cr carbides</td>
<td>Basically ferritic with tiny Cr carbides</td>
</tr>
<tr>
<td>6.23</td>
<td>Fe-0.2 % C-2 % Cr</td>
<td>Fine-grained ferrite with dark pearlite and a number of Cr carbides</td>
<td>Fine-grained ferrite with dark pearlite and a number of Cr carbides</td>
<td>Fine-grained ferrite with dark pearlite and a number of Cr carbides</td>
<td>Fine-grained ferrite with dark pearlite and a number of Cr carbides</td>
</tr>
<tr>
<td>6.24</td>
<td>Fe-0.2 % C-1 % Cr-2%Ni</td>
<td>Basically ferritic and pearlite and un resolved pearlite with pores</td>
<td>Basically ferritic and pearlite and un resolved pearlite with few grains of fine austenite</td>
<td>Basically ferritic and pearlite with a few grains of fine austenite</td>
<td>Ferritic structure with some massive carbide particles distributed along the grain boundaries with numerous round and elongated pores.</td>
</tr>
<tr>
<td>6.25</td>
<td>Fe-0.2 % C-1 % Cr-2%Ni-1.5%Mo</td>
<td>Basically ferritic and pearlite with pores</td>
<td>Basically ferritic and pearlite with a few grains of fine austenite</td>
<td>Basically ferritic and pearlite with a few grains of fine austenite</td>
<td>Ferritic structure with some massive carbide particles distributed along the grain boundaries with Numerous round and elongated pores.</td>
</tr>
</tbody>
</table>
(a) As-Sintered

(b) Cold Upsetting

(c) Hot Upsetting

(d) Cold Repressing

Figure 6.18. Photomicrographs of Fe-0.2%C P/M steel
Figure 6.19. Photomicrographs of Fe-0.2%C-2%Ni P/M steel
Figure 6.20. Photomicrographs of Fe-0.2%C-2%Ni-1.5%Mo P/M sSteel
Figure 6.21. Photomicrographs of Fe-0.2%C-2%Ni-3%Mo P/M steel

(a) As-Sintered
(b) Cold Upsetting
(c) Hot Upsetting
(d) Cold Repressing
Figure 6.22. Photomicrographs of Fe-0.2%C-1%Cr P/M steel
Figure 6.23. Photomicrographs of Fe-0.2%C-2%Cr P/M steel
Figure 6.24. Photomicrographs of Fe-0.2%C-1%Cr-2%Ni P/M steel
Figure 6.25. Photomicrographs of Fe-0.2%C-1%Cr-2%Ni-1.5%Mo P/M steel
6.7. Plasticity Theory and Formability

Forging of metal powder preforms is of considerable interest to the producers of engineering components. The successful production of parts by forging depends on factors such as careful control of the deformation process to ensure uniform densification, crack avoidance and finally elimination of flash formation. Due to the presence of porosity in powder materials, their plastic deformation behaviour is different from that of cast and wrought conventional materials. The porous materials are spread in the lateral direction to a lesser degree compared to conventional materials. For rational design of forging processes, it is necessary to obtain a quantitative understanding of this plastic deformation. Several researchers have studied the plastic behaviour of porous materials and have developed suitable theoretical models.

Khun and Downey [23] have developed plasticity equations for the plastic deformation of porous materials. For developing plasticity theory for any material, it is first necessary to establish a yield criterion and then flow rule from which the stress-strain relations are derived. For a fully dense material, the yielding is given to be a function only of the second invariant of the stress deviator, \( J_2 \)

\[
f = (3 J_2) ^{1/2}
\]

6.2

Where, \( J_2 = \frac{(\sigma_1-\sigma_2)^2 + (\sigma_2-\sigma_3)^2 + (\sigma_3-\sigma_1)^2}{6} \)

6.3

\( \sigma_1, \sigma_2 \) and \( \sigma_3 \) are principal stresses, \( f \) is a yield criterion.
For conventional materials the hydrostatic stress does not cause yielding, but for the powder materials this will cause yielding. Therefore, the yield criterion for powder materials must be a function of hydrostatic stress and deviatoric stress.

\[ f = f(J_1, J_2) \]  \hspace{1cm} (6.4)

Where,

\[ J_1 = \text{Hydrostatic stress} = (\sigma_1 + \sigma_2 + \sigma_3)/3 \]  \hspace{1cm} (6.5)

Further it is convenient to express the above yield criterion by relating the first invariant of stress tensor \( J_1 \) to \( J_2 \) and the second invariant of stress, \( J_2 \), such as

\[ f = f(J_2, J_2') \]  \hspace{1cm} (6.6)

Where, \( J_2 = -(\sigma_1 \sigma_2 + \sigma_2 \sigma_3 + \sigma_3 \sigma_1) \)  \hspace{1cm} (6.7)

The yield criterion for powder materials reflects the influence of increasing density on the flow stress and in fact, reduces to the yield criterion for a conventional material [equation 6.3], as full density is approached.

The yield criterion proposed by Khun and Downey is:

\[ f' = (3J'_2 - (1 - 2u)J_2) \]  \hspace{1cm} (6.8)

where, \( u \) - Poisson’s ratio.

From the year 1971 to 1984 various researchers such as Green [39], Moriya Oyane et al [44&45], developed plasticity theory for porous powder materials.

Doraivelu et al [46], consolidated the various yield functions developed for P/M alloys by various researchers and they themselves developed a new yield function for P/M alloys.
Their new yield function illustrated in terms of principal stress and relative density ‘R’ is follows:

\[ \sigma_1^2 + \sigma_2^2 + \sigma_3^2 - R^2 (\sigma_1 \sigma_2 + \sigma_2 \sigma_3 + \sigma_3 \sigma_1) = (2 R^2 - 1) Y_0^2 \]

They further developed the three-dimensional yield surface using the above equation and computer graphics software namely, MOVIE.BYU, developed by Brigham Young University, USA.

**6.7.1. Forming Limit or Formability**

Most bulk forming processes such as forging, rolling extrusion involve stress states that are predominantly compressive; however some secondary tensile stresses at specific locations in any of these processes can develop leading to fracture initiation. Formability determines the extent of deformation or the limit of deformation of a material in forming processes such as forging, rolling, extrusion etc.

Vujovic and Shabaik [54] proposed a forming limit criterion for bulk metal working processes, based on the magnitude of the hydrostatic stress component and the effective stress. They further proposed a formability criterion, using the parameter \( \beta \), defined as follows:

\[ \beta = \frac{3\sigma_m}{\bar{\sigma}} \]

where,

- \( \sigma_m = \) Mean or Hydrostatic stress component
- \( \bar{\sigma} = \) Effective stress component
Abdel-Rahman and El-Sheikh [55] have developed basic relations for the state of stress in a homogeneous compression of porous materials. As compression continues, the final diameter continues to increase and the corresponding hoop strain- which is a tensile strain- increases until it reaches the material fracture limit. Once the fracture is initiated, the forming-limit strain is the same as the effective strain at fracture. Abdel-Rahman and El-Sheikh [55], referred the parameter proposed by Vujovic and Shabaik [54] for their analysis for the fracture limit. They considered the Khun and Downey theory and Whang and Kobayashi theory for the deformation characterization of the P/M preforms.

Narayanasamy et al [56-58] used the workability studies introduced by Vujovic and Shabaik [54], Abdel-Rahman and El-Sheikh [55] and simplified the expressions for the calculation of hoop stress, hydrostatic stress or mean stress, effective stress, hoop strain, mean strain, effective strain.

The following are the mathematical expressions from the literature utilized for calculating various formability parameters.

\[
\text{Axial Stress } \sigma_a = \frac{\text{AppliedLoad}}{\text{Area}} = \frac{4P}{\pi D_{ac}^2} \tag{6.11}
\]

Where \( D_{ac} \) = Average contact diameter = \( \frac{D_{uc} + D_{lc}}{2} \) \tag{6.12}

\[
D_a = \text{Average Diameter} = \frac{D_{uc} + D_{lc} + D_{bulge}}{2} \tag{6.13}
\]
where,

\[ P = AppliedLoad \]
\[ D_o = AverageDiameter \]
\[ D_{uc} = UppersideContactDiameter \]
\[ D_{lc} = LowersideContactDiameter \]
\[ D_{bulge} = BulgeDiameter \]

The radial stress \( \sigma_r \) and Hoop stress \( \sigma_\theta \) can be determined from the known value of Poisson’s ratio, fractional density by the following expression,

\[
\nu = \frac{(2 + R^2)\sigma_\theta - R^2(\sigma_o + 2\sigma_\theta)}{(2 + R^2)\sigma_o - R^2(\sigma_o + 2\sigma_\theta)}
\]

\[ \text{Poisson's ratio } \nu = 0.5(R)^n \quad (\text{Khun & Downey[23]}) \]

\[ \text{Where, } R = \text{Fractional theoretical Density}, \]

\[ n = \text{Power law exponent, } n=1.92 \text{ for cold working and } n=2 \text{ for Hot working} \]

Hoop stress \( \sigma_\theta = \frac{2\nu + R^2}{2 - R^2 + 2R^2\nu} \sigma_o \]

Formability stress index \( \beta = \frac{3\sigma_m}{\sigma_{eff}} \quad (\text{Vujovic and Shabaik [54]}) \]

The hydrostatic stress or mean stress \( \sigma_m = \frac{\sigma_r + \sigma_\theta + \sigma_o}{3} \)

For triaxial stress state, the radial component of stress \( \sigma_r = \sigma_\theta \)

Therefore, \( \sigma_m = \frac{\sigma_o + 2\sigma_\theta}{3} \)
The effective stress for triaxial stress state under upsetting,

\[ \sigma_{\text{eff}} = \left( \frac{\sigma_a^2 + 2\sigma_a^2 - R^2(\sigma_a \sigma_{\theta} + \sigma_a^2 + \sigma_{\theta}^2)}{2R^2 - 1} \right)^{\frac{1}{2}} \] -----------------------------6.20

True Axial Strain \[ \varepsilon_a = \ln\left( \frac{h_o}{h_d} \right) \] -----------------------------6.21

Where, \( h_o = \text{OriginalHeight} \) and \( h_d = \text{DeformedHeight} \)

Hoop strain \[ \varepsilon_{\theta} = \ln\left( \frac{2D_{\text{bulge}}^2 + \left( D_{\text{UC}} + D_{\text{LC}} \right)}{3D_i^2} \right) \] -----------------------------6.22

Formability Strain index or Strain formability parameter \[ \alpha = \frac{3\varepsilon_m}{\varepsilon_{\text{eff}}} \] -----------------------------6.23

(Narayanasamy et al.[56-58])

The mean strain \[ \varepsilon_m = \left( \frac{\varepsilon_r + \varepsilon_a + \varepsilon_{\theta}}{3} \right) \] -----------------------------6.24

For triaxial stress state conditions \( \varepsilon_r = \varepsilon_{\theta} \) (for upsetting)

For repressing \( \varepsilon_r = \varepsilon_{\theta} = 0 \)

Therefore, \[ \varepsilon_m = \left( \frac{\varepsilon_a + 2\varepsilon_{\theta}}{3} \right) \] -----------------------------6.25

\[ \varepsilon_{\text{eff}} = \left[ \left( \frac{2}{3(2 + R)} \right) \{ (\varepsilon_a - \varepsilon_{\theta})^2 + (\varepsilon_{\theta} - \varepsilon_a)^2 \} + \left( \frac{(\varepsilon_a + 2\varepsilon_{\theta})^2}{3} \right) \{ 1 - R^2 \} \right]^{\frac{1}{2}} \] -----------------------------6.26

(Narayanasamy et al. [56-58])

In the present work, the axial stress, true height strain, radial stress, strain, hoop stress, strain, the effective stress and strain have been calculated for the various alloys by using
the above equations. From these values the stress, strain index or stress and strain formability parameters have been calculated for each level of axial deformation during cold and hot forging operations up to the maximum deformation points. These formability parameters are dimensionless parameters, which indicate the maximum stress and the strain corresponding to fracture. Further, these parameters also indicate the ability of the material to take the exact shape during forging and to decide the capacity of the forging press required for producing parts or components of given geometry.

The formability index is correlated for cold upset, cold repressed and hot upset forged preforms with the fractional theoretical density to facilitate the study of the impact of various alloying elements on formability. Lower stress and strain formability index values are an indication of poor formability behaviour and a higher index value indicates good formability of the materials. It is also employed for specifying fracture limit of formability.

Table 6.1. shows the stress formability index and strain formability index of various alloys during cold upsetting, cold repressing. Further strain formability index values for hot upsetting are also depicted in the same table.

6.7.1.1. Formability of Cold Upset Forged and Cold Repressed Preforms

Stress formability index vs. strain formability index has been correlated for cold upset forged and cold repressed preforms, which are shown in Figures 6.26 & 6.27 to facilitate the study of the impact of the various alloying elements on formability. Lower stress and
strain formability index values are an indication of poor formability behaviour and a higher formability index values indicates good formability of the material.

From the plot shown in Figure 6.34, the formability index of the various alloys during cold upsetting is almost of the same level except for Fe-0.2%C-1%Cr-2%Ni and Fe-0.2%C-1%Cr-2%Ni-1.5%Mo steel. The addition of Cr with Ni & Mo enhances the formability of the steel. During cold pressing, preform containing Ni and Ni-Mo shows poor formability behaviour. Addition of alloying element Cr to steel containing Ni & Mo is observed to enhance the formability, which is evident from the plot shown in Figure 6.27. Comparing the Figures 6.26 & 6.27, the strain formability index is lower for cold repressed preforms. This is due to the absence of lateral strain. This lower strain formability index for the corresponding higher stress formability index dictates the manufactures to select higher capacity of forging press compared to cold upsetting.

![Figure 6.26. Formability index of the various alloys during cold upsetting](image-url)
Figure 6.27. Formability index of the various alloys during cold repressing

6.8. Mechanical properties

A comparison of the various mechanical properties such as tensile, impact and hardness values of the various alloys under study is presented in Table 6.6.

<table>
<thead>
<tr>
<th>Sl.No</th>
<th>Alloy Composition</th>
<th>Ultimate Strength, MPa</th>
<th>Breaking Strength, MPa</th>
<th>Yield Strength, MPa</th>
<th>% Elongation in Length</th>
<th>% Reduction in Area</th>
<th>Hardness HRB</th>
<th>Impact Strength, J</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fe-0.2% C</td>
<td>453</td>
<td>434</td>
<td>179</td>
<td>18.5</td>
<td>34.1</td>
<td>72</td>
<td>38</td>
</tr>
<tr>
<td>2</td>
<td>Fe-0.2% C-2% Ni</td>
<td>548</td>
<td>304</td>
<td>192</td>
<td>14.1</td>
<td>22.6</td>
<td>74</td>
<td>24</td>
</tr>
<tr>
<td>3</td>
<td>Fe-0.2% C-2% Ni-1.5% Mo</td>
<td>608</td>
<td>581</td>
<td>227</td>
<td>11.3</td>
<td>15.1</td>
<td>85</td>
<td>22</td>
</tr>
<tr>
<td>4</td>
<td>Fe-0.2% C-2% Ni-3% Mo</td>
<td>521</td>
<td>385</td>
<td>250</td>
<td>10.6</td>
<td>14.2</td>
<td>89</td>
<td>20</td>
</tr>
<tr>
<td>5</td>
<td>Fe-0.2% C-1% Cr</td>
<td>1282</td>
<td>1073</td>
<td>530</td>
<td>10.1</td>
<td>14</td>
<td>92</td>
<td>19</td>
</tr>
<tr>
<td>6</td>
<td>Fe-0.2% C-2% Cr</td>
<td>1373</td>
<td>1093</td>
<td>580</td>
<td>9.1</td>
<td>12.6</td>
<td>95</td>
<td>14</td>
</tr>
<tr>
<td>7</td>
<td>Fe-0.2% C-1% Cr-2% Ni</td>
<td>1180</td>
<td>1069</td>
<td>504</td>
<td>12.9</td>
<td>16.5</td>
<td>82</td>
<td>21</td>
</tr>
<tr>
<td>8</td>
<td>Fe-0.2% C-1% Cr-2% Ni-1.5% Mo</td>
<td>637</td>
<td>570</td>
<td>273</td>
<td>7.13</td>
<td>11.8</td>
<td>84</td>
<td>13</td>
</tr>
</tbody>
</table>
During the tensile response none of the alloys exhibited localized necking like a conventional material. However, the plain carbon steel specimen exhibited a cup and cone type fracture with extensive, localized necking. The alloy steel specimens have undergone shearing type of fracture with associated ductility. It is evident from the table that higher tensile strength and hardness values are exhibited by the forged alloy steels compared to the forged plain carbon steel (Fe-0.2%C). The microstructures of the forged low alloy steels revealed the presence of bainite, pearlite and retained austenite in ferritic matrix. Bainite and austenite phases are known to influence the tensile strength of ferrous alloys. Therefore, the forged steels containing Cr and Mo have exhibited greater strengths and hardness. The hardness of the plain carbon steel specimen is the lowest compared with that of the other four alloy steels, while the reverse trend has been observed with respect to impact strength. The ductility of a material is indicated by its percentage reduction in area (%RA) and percentage elongation in length (%EL), evaluated by the standard uniaxial tensile test.

Among the eight alloys considered, the forged plain carbon steel is found to possess lowest tensile strength of about 453 MPa, impact strength of 38J and highest ductility, which is inferred from the highest values of %EL and %RA for this steel. It is also inferred from the fractograph (Figure 6.29.a.1) of this steel, that the type of fracture is pure ductile. This is evident from the presence of numerous dimples along with fine and rounded pores. Ductile fracture is also supported by the occurrence of microvoid coalescence, which has led to the presence of larger size dimples as observed in the fractograph. The presence of deep pit like structure in the fractograph is an indication of formation of ridges during the cup and cone fracture in the case of the plain carbon steel.
Lower tensile strength, higher ductility and higher impact strength associated with the plain carbon steel can be attributed to the ferritic-pearlitic structure with larger ferrite grain size as shown in Figure 6.28.a.1.

Addition of 2% Cr alone to the plain carbon steel has led to enhancement of tensile strength by about 65% and the hardness by 32% in comparison with plain carbon steel. Among the alloys under investigation Fe-0.2%C-2%Cr steel shows highest tensile strength of about 1373MPa. Further, addition of 1%Cr alone to plain carbon steel shows next higher tensile strength of about 1282MPa. Lower %EL and %RA of this alloy indicates lower level of ductility. The yield strength and breaking strength values for these alloys are also highest levels compared to other alloy steels and plain carbon steel undertaken for the present study. Lower impact strength of these alloys compared to plain carbon steel is in conformity with the fact that strength and impact values are in inverse proportion. The microstructures of the Fe-0.2%C2%Cr and Fe-0.2%C-1%Cr steels depicted in Figures 6.28.b.1. & 2. indicates a basic ferritic structure, since, Cr is a known ferrite stabilizer. A few carbides of Cr as well as numerous bainites are also observed in the microstructure. The presence of carbide and bainite accounts for the high strength and hardness of these alloys. The carbides of Cr are observed to be precipitated along the grain boundaries along with bainite. It is reported that the alloying element Cr has a tendency to get solution hardened by carbide precipitation [73]. The fractographs of these alloys shown in Figures 6.29.b.1. & 2. exhibit numerous dimples along with a number of secondary cracks. Further, numerous voids are also observed. These voids are indicative of the removal of Cr carbide particulates through pulling off under heavy tensile loading conditions. It is also evident that secondary cracks have originated from these voids,
which have acted as stress raisers. It can be concluded that the type of fracture is mixed mode i.e., both brittle and ductile fracture in the alloy Fe-C-Cr.

Addition of 2%Ni, to Fe-0.2%C-1%Cr results in a small reduction in tensile strength and hardness. Ni, being an austenite stabilizer, has led to the retention of a few austenite grains, in a basically ferritic matrix, due to which the reduction in ultimate tensile strength (UTS), yield strength (YS), breaking strength (BS) and hardness are observed in the case of Fe-0.2%C-1%Cr-2%Ni. However, there is no notable increase in impact strength of this alloy compared to Fe-0.2%C-1%Cr. The microstructure of this alloy is predominantly ferritic-bainitic with retained austenitic structure as depicted in Figure 6.28.b.3. The corresponding %EL and %RA values of this alloy are higher than that of Fe-0.2%C-1%Cr and still lower than that of the plain carbon steel. The fractograph of Fe-C-Cr-Ni alloy (Figure 6.29.b.3.) indicates a mixed mode of fracture, which is very similar to that of Fe-C-Cr alloy.

Further, addition of 1.5%Mo to Fe-0.2%C-1%Cr-2%Ni lowers the tensile strength by about 50% compared to Fe-0.2%C-1%Cr steel. The %EL and %RA values are the lowest compared to all alloys and plain carbon steel undertaken for the present study. The lower %RA & %EL can be attributed to the presence of carbides of Cr & Mo. The fractograph (Figure 6.29.b.4.) shows numerous voids and secondary micro cracks which point out to a mixed mode of fracture of this alloy.

Presence of 2%Ni in the plain carbon steel without addition of Cr has led to notable reduction in tensile strength and hardness values as compared to the corresponding values of the Cr alloyed steel. Therefore, it is evident that Cr as alloying element has led to
improvements in both tensile and hardness values. Adding Ni alone to Fe-0.2%C is found to result in marginal increase in the impact strength of the alloy, because Ni is known to improve impact resistance of steels. Further, a marginal improvement in impact strength could also be observed due to addition of Ni to the Cr alloyed steel. Figure 6.28.a.2 illustrates the microstructure of the hot forged Fe-0.2%C-2%Ni P/M steel. The structure obtained is ferritic with bainites distributed along the grain boundaries of the ferrite grains. Further, a few retained austenite grains are also observed in the microstructure. The alloy with Ni has higher %EL and %RA as compared to the alloy with the addition of Cr. Numerous micro voids and equiaxed dimples along with some distributed secondary cracks are observed in the fractograph of Fe-0.2%C-2%Ni, which is shown in Figure 6.29.a.2. It is concluded that the type of fracture in this alloy is mainly ductile in nature.

The present study also considers the effect of addition of either 1.5% Mo or 3%Mo to the Fe-0.2%C-2%Ni steel on its tensile, hardness and impact properties. Adding Mo to Fe-C-Ni alloy improves the tensile and hardness properties marginally with a small reduction in %EL and %RA. Mo is a known ferrite stabilizer as well as carbide former. In combination with Ni, presence of Mo in this steel has resulted in a microstructure, which is ferritic with distributed Mo carbide, and spheroidal bainites (Figures 6.28.a.3. & 4.). Further, during sintering and hot forging operations, the Mo particles are likely to combine with diffused carbon, forming Mo carbide, whose presence in the alloys may account for the reduction in impact strength as well as improved strength compared to plain carbon steel with and without Ni. The above-mentioned observations are suggestive of the brittleness of this alloy. The impact strengths of the Fe-C-Ni-Mo low alloy steels
are reduced marginally due to the presence of Mo carbides. From the fractographs of forged Ni-Mo steel (Figures 6.29.a.3. & 4.), it is clear that, the presence of large number of dimples along with deep secondary cracks points to mixed mode of fracture. Further, initiation of fracture could have taken place at micro pores and at voids left out by the pulling off of particulates.

It has also been observed from the results of the study that the tensile strength values of all the eight sintered and forged steels were comparable with that of commercial low alloy wrought steels of near – similar compositions.

It is concluded that among the alloys considered for the present research work, the Cr alloyed P/M steel exhibits the highest UTS and YS values with corresponding impact strength being the lowest. Further, addition of Ni to Fe-0.2%C lowers the UTS and hardness values, but enhances %RA & % EL. Presence of Mo in the Fe-0.2%C-2%Ni without any Cr addition is found to result in increase in strength and hardness values marginally.

Table 6.7 summarises the important observations on the photomicrographs of the tensile samples of the different alloys.
Figure 6.28.a. Microstructures of tensile tested samples
1) Fe-0.2%C  
2) Fe-0.2%C-2%Ni  
3) Fe-0.2%C-2%Ni-1.5%Mo  
4) Fe-0.2%C-2%Ni-3%Mo
Figure 6.28.b Microstructures of tensile tested samples

1) Fe-0.2%C-1%Cr  
2) Fe-0.2%C-2%Cr  
3) Fe-0.2%C-1%Cr-2%Ni  
4) Fe-0.2%C-1%Cr-2%Ni-1.5%Mo
### Table 6.7 Summaries of the microstructures of the tensile samples

<table>
<thead>
<tr>
<th>Sl.No</th>
<th>Fig.No</th>
<th>Alloy Composition</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.28.a.1</td>
<td>Fe-0.2%C</td>
<td>Ferritic-pearlitic structure with larger ferrite grain size</td>
</tr>
<tr>
<td>2</td>
<td>6.28.a.2</td>
<td>Fe-0.2%C-2%Ni</td>
<td>Ferritic with bainites distributed along the grain boundaries of the ferrite</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>grains. Further, with few austenite grains.</td>
</tr>
<tr>
<td>3</td>
<td>6.28.a.3</td>
<td>Fe-0.2%C-2%Ni-1.5%Mo</td>
<td>Ferrite-austenitic structure with distributed Mo carbide, and spheroidal</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>bainites.</td>
</tr>
<tr>
<td>4</td>
<td>6.28.a.4</td>
<td>Fe-0.2%C-2%Ni-3%Mo</td>
<td>Ferrite-austenitic structure with lots of distributed Mo carbide, and spheroidal</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>bainites.</td>
</tr>
<tr>
<td>5</td>
<td>6.28.b.1</td>
<td>Fe-0.2%C-1%Cr</td>
<td>Ferritic structure, few carbides of Cr have been precipitated along the grain</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>boundaries along with bainite</td>
</tr>
<tr>
<td>6</td>
<td>6.28.b.2</td>
<td>Fe-0.2%C-2%Cr</td>
<td>Ferritic structure, more carbides of Cr have been precipitated along the grain</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>boundaries along with bainite</td>
</tr>
<tr>
<td>7</td>
<td>6.28.b.3</td>
<td>Fe-0.2%C-1%Cr-2%Ni</td>
<td>Ferritic-bainitic with retained austenitic structure</td>
</tr>
<tr>
<td>8</td>
<td>6.28.b.4</td>
<td>Fe-0.2%C-1%Cr-2%Ni-1.5%Mo</td>
<td>Ferritic-bainitic with retained austenitic structure along with distributed</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Cr and Mo carbides</td>
</tr>
</tbody>
</table>

### 6.9. Fractograph & Energy Dispersive X-ray analysis EDX Report

The summaries of the fractographs of tensile samples are shown in Table 6.8.

Figure 6.30. Shows the sum spectra of EDX report.
Figure 6.29.a. Fractographs of tensile tested samples
1) Fe-0.2%C
2) Fe-0.2%C-2%Ni
3) Fe-0.2%C-2%Ni-1.5%Mo
4) Fe-0.2%C-2%Ni-3%Mo
Figure 6.29. Fractographs of tensile tested samples

- e) Fe-0.2%C-1%Cr
- f) Fe-0.2%C-2%Cr
- g) Fe-0.2%C-1%Cr-2%Ni
- h) Fe-0.2%C-1%Cr-2%Ni-1.5%Mo
Table 6.8 Summaries of the fractographs of the tensile samples

<table>
<thead>
<tr>
<th>Sl.No</th>
<th>Fig.No</th>
<th>Alloy Composition</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.29.a.1</td>
<td>Fe-0.2%C</td>
<td>Micro-void coalescence, Numerous dimples along with fine and rounded pores with deep pit like structure. Cup and cone type of fracture. Ductile fracture.</td>
</tr>
<tr>
<td>2</td>
<td>6.29.a.2</td>
<td>Fe-0.2%C-1%Cr</td>
<td>Micro-void coalescence, Numerous dimples along with a number of secondary cracks. Mixed mode of fracture</td>
</tr>
<tr>
<td>3</td>
<td>6.29.a.3</td>
<td>Fe-0.2%C-2%Cr</td>
<td>Numerous dimples along with a number of secondary cracks. Mixed mode of fracture</td>
</tr>
<tr>
<td>4</td>
<td>6.29.a.4</td>
<td>Fe-0.2%C-1%Cr-2%Ni</td>
<td>Mixed mode of fracture-more of ductile – due to the presence of extensive dimples</td>
</tr>
<tr>
<td>5</td>
<td>6.29.b.1</td>
<td>Fe-0.2%C-1%Cr-2%Ni-1.5%Mo</td>
<td>Mixed mode of fracture-more of ductile – due to the presence of extensive dimples</td>
</tr>
<tr>
<td>6</td>
<td>6.29.b.2</td>
<td>Fe-0.2%C-2%Ni</td>
<td>Numerous micro voids and equiaxed dimples along with some distributed secondary cracks- Ductile Fracture.</td>
</tr>
<tr>
<td>7</td>
<td>6.29.b.3</td>
<td>Fe-0.2%C-2%Ni-1.5%Mo</td>
<td>Mixed mode of fracture due to presence of fine dimples and quasi-cleavages</td>
</tr>
<tr>
<td>8</td>
<td>6.29.b.4</td>
<td>Fe-0.2%C-2%Ni-3%Mo</td>
<td>Mixed mode of fracture due to presence of fine dimples and quasi-cleavages</td>
</tr>
</tbody>
</table>
Figure 6.30.a. Sum spectra of EDX report of Fe-0.2% C-2% Ni low alloy P/M steel

Figure 6.30.b. Sum spectra of EDX report of Fe-0.2% C-2% Ni-1.5% Mo low alloy P/M steel
Figure 6.30.c. Sum spectra of EDX report of Fe-0.2% C-2% Ni-3% Mo low alloy P/M steel

Figure 6.30.d. Sum spectra of EDX report of Fe-0.2% C-1% Cr low alloy P/M steel
Figure 6.30.e. Sum spectra of EDX report of Fe-0.2% C-2% Cr low alloy P/M steel

Figure 6.30.f. Sum spectra of EDX report of Fe-0.2% C-1% Cr-2%Ni low alloy P/M steel
6.9. Summary

The results of the present investigations regarding the workability, plastic deformation, densification and mechanical properties such as tensile strength, ductility, hardness and toughness were explained in this chapter with interpretation of microstructures and fractographs. The study of these characteristics is very much important for the selection of materials for any engineering design application. These results are established after careful consideration of the standard experimental procedures and repeated for the repeatability and acceptability of the reported values.