1. Introduction

To improve both the fuel efficiency and crash worthiness of automobile, steels are required which combine high tensile strength with good formability. Steels characterized by a microstructure consisting of a dispersion of hard martensite phase in a soft ductile ferrite are commonly referred to as “dual phase steels”. The term “dual phase” refers to the presence of essentially two phases, ferrite and martensite, in the microstructure, although small amounts of bainite, pearlite and retained austenite may also be present.

Generally, dual phase steels can be manufactured in two different ways: Hot Rolled Dual Phase (HRDP) and Cold Rolled Dual Phase (CRDP). In the first case dual phase structure is developed during cooling after hot rolling, whereas in the latter dual phase structure is formed after intercritical annealing of a previously rolled product. In either case, cooling within an appropriate range of rates allows a fraction of the austenite to transform to ferrite and another fraction to martensite. Intermediate transformation products, pearlite and bainite, are generally avoided. A favorable combination of strength and ductility can be obtained by developing a dual phase or multiphase microstructure in steels. In the past two decades dual phase steels have received great attention because of their characteristic mechanical properties. It has been established that at a given tensile strength level, these dual phase steels have formability superior to commercially available high strength low alloy steels.

Although a significant amount of research activity has taken place in the development of ferrite–martensite dual phase steels, there is little reported work on the ferrite–bainite type dual phase steels. Again, although plenty of work has been carried out on CRDP steels, hardly any serious attention has been paid to the HRDP steels. In order to produce HRDP steels the steel chemistry plays very important role. In lean HRDP steels it would be rather difficult to produce a ferrite–martensite distribution, and a ferrite–bainite phase mixture may be obtained instead. A ferrite–bainite dual phase steel does not exhibit the typical continuous yielding behavior, characteristic of the ferrite–martensite dual phase steels. It would be interesting to see if the presence of even a small amount of martensite in a ferrite–bainite dual phase steel will make it exhibit the characteristic properties of dual phase steels, such as continuous yielding behavior and, thereby, make it useful for the automobile industry. It was with this idea that the present work was undertaken.

2. Experimental Procedure

The chemical compositions of the four DP steels used in this study are presented in Table 1. The steels were melted in the form of 50 kg ingots in an induction furnace. These were forged to remove the cast structure. The forged materials were soaked at 1 200°C for 3 h, and then hot rolled in an instrumented laboratory rolling mill. The details of the
hot rolling schedule are given in Fig. 1. The steels with initial thickness of 70 mm were first rolled to 25 mm thickness in 5 passes and then further rolled to 5 mm thickness in 4 passes. The amounts of deformation given in the two stages were 64% and 80% respectively. The finish rolling temperature (FRT) was kept within 860–875°C for all the steels so that rolling was completed in the austenitic region. The FRT was decided on the basis of the calculated values of the Ar₃ temperatures of the steels using Andrew’s equation and the calculated Ar₃ temperatures for steels A, B, C and D are 852°C, 837°C, 849°C and 851°C respectively. Metallographic specimens were cut out from hot rolled materials and were prepared using standard metallographic polishing techniques. The samples were finally etched with La Pera reagent to identify the different phases. Micrographs were observed on the longitudinal sections. In order to confirm the identity of different phases, microhardness measurements were also carried out using Leitz RZD micro hardness tester. The microstructures were analysed with the help of Leica Q-Win Digital Image Analysis software.

Tensile tests were carried out in an INSTRON 4210 tensile testing machine on samples from all the four hot rolled steels. Standard ASTM specimens of rectangular cross section having 25 mm width and 50 mm gauge length were used for the purpose. A cross-head speed of 10 mm/min was maintained upto the yield point and, thereafter speed of 50 mm/min was maintained upto fracture. The strain to necking in each specimen was recorded using an extensometer. From the tensile tests the yield strength, ultimate tensile strength, percent total elongation and percent reduction in area were measured. The fractured surfaces of the tensile samples were examined in a Scanning Electron Microscope (JEOL 6400).

Standard sub-size samples (as per ASTM E23-02a) from the four hot rolled steels were made for Charpy impact testing. At least three specimens were used for each experiment. Testing was carried out in a Mohr & Federhaff (PSW-30) Charpy Impact Tester at both room and liquid nitrogen temperatures. The micro-hardness values for a particular phase was found to vary for the different steel compositions. Steel A exhibited the lowest hardness value for all the three phases, whereas the corresponding values were the highest in steel D. Among the three phases, ferrite showed the minimum hardness and martensite the maximum with bainite lying in between.

Some typical TEM microstructures of the four steels are depicted in Figs. 3(a)–3(d). In general, the ferrite phase in all the steels show a cell-like structure, both close to and away from the neck region of tensile samples. However the average cell size is larger and the dislocation density appears to be much less in the foil made from a region away from the neck. These are illustrated for steel A in Figs. 3(a) and 3(b). Figure 3(c) shows a region in steel C which is made up of the ferrite phase and a profusion of bainite platelets. The dislocation density in the ferrite adjoining the bainitic regions is low. This is true in case of all the four steels. Figure 3(d) shows an area in steel B where all the three phases—ferrite, bainite and martensite—are found to co-exist. It is clear from this micrograph that the ferritic regions adjoining the martensite contain a high density of dislocations, unlike the ferrite which forms close to the bainitic regions.

### Table 2. Volume fraction of different phases and corresponding microhardness values (Hv).

<table>
<thead>
<tr>
<th>Grade</th>
<th>Ferrite</th>
<th>Bainite</th>
<th>Martensite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel A</td>
<td>0.46</td>
<td>183</td>
<td>0.48</td>
</tr>
<tr>
<td>Steel B</td>
<td>0.51</td>
<td>198</td>
<td>0.47</td>
</tr>
<tr>
<td>Steel C</td>
<td>0.23</td>
<td>207</td>
<td>0.74</td>
</tr>
<tr>
<td>Steel D</td>
<td>0.32</td>
<td>216</td>
<td>0.65</td>
</tr>
</tbody>
</table>
3.2. Mechanical Properties

The engineering stress–strain curves upto the onset of necking are shown in Fig. 4. It is clear that all the four steels show a continuous yielding behavior, in spite of their rather low martensite content. The room temperature tensile properties of the four hot rolled steels as measured from these plots are given in Table 3. There are significant differences in the values of the tensile properties of these steels. For example, steel A has the lowest yield and tensile strengths, while steel D possesses the highest yield and tensile values among the four steels. All the steels show reasonably high ductility and the YS/UTS ratio lies between

Fig. 2. Optical micrographs of different hot rolled steels etched with La Pera reagent: (a) steel A, (b) steel B, (c) steel C and (d) steel D.

Fig. 3(a). TEM micrographs taken from steel A at a region away from the neck showing cell structure.

Fig. 3(b). TEM micrographs taken from steel A at a region near the neck showing high density of dislocations.
0.55 and 0.65. The plot depicting tensile strength vs. %elongation for the four steels is shown in Fig. 5. It can be observed from this plot that the best combination of tensile strength and percentage elongation is found for steel B, although steel D shows the highest value for the tensile strength.

The Charpy impact toughness values for the steels at room temperature and at \(-40^\circ\text{C}\) are given in Table 4. The tensile strength vs. Charpy impact energy (at room temperature and at \(-40^\circ\text{C}\)) is plotted in Fig. 6. It is clear from Table 4 that at both the temperatures steel A has the highest values (56.8 and 21.6 J) and steel B has the lowest Charpy impact energy values (33.9 and 6.7 J) among the four steels. Steels C and D show nearly similar toughness values and these lie in between those of steels A and B. The results of the Charpy tests carried out at \(-40^\circ\text{C}\) show that there is a significant drop in the impact values for the four steels at low temperature. Although no particular steel possesses the highest values of all the three parameters—tensile strength, %elongation and charpy impact values, steel D appears to
have the best combination of all the three properties among the four steels.

3.3. Strain Hardening Behavior

The differential Crussard-Jaoul (C-J),8–10) Hollomon11) or the modified C-J analysis12) has been used to critically analyze the tensile stress-strain data. The first of these analytical methods has been used in the present case for understanding the strain hardening behavior of the four experimental steels. This method is based on the power Ludwik relation,

\[ \sigma = \sigma_0 + k \varepsilon^n \] ............................................(1)

where \( \sigma \) is the true stress, \( \varepsilon \) is the true strain, \( n \) is the work hardening exponent, and \( \sigma_0 \) and \( k \) are material constants.

The logarithmic form of Eq. (1), after differentiation with respect to \( \varepsilon \), is

\[ \ln(d\sigma/d\varepsilon) = \ln(kn) + (n-1) \ln \varepsilon .................(2) \]

In a \( \ln(d\sigma/d\varepsilon) + \ln \varepsilon \) plot, the slope of the line gives \((n-1)\), while its intersection with \( \ln \varepsilon = 0 \) provides \((kn)\), so that both \( n \) and \( k \) and, therefore, \( \sigma_0 \) can be determined.

The results of the differential C-J analysis for the four steels are shown in Fig. 7. These plots clearly indicate a two stage deformation behavior with a decrease in the \( n \) value with increasing strain, irrespective of the composition. The \( n \) value ranges between 0.53 to 0.7 in the first deformation stage and between \(-1.08 \) to 0.25 in the second stage.

4. Discussion

4.1. Structure–Property Correlation

The four steels under investigation are basically ferrite–bainite dual phase steels with a maximum of around 6% of the third phase, which is martensite. In steels A and B, the ferrite and bainite phases are present in nearly equal amounts. Steel C has the maximum amount of bainite (74%) while steel D has a slightly lower amount (65%) of this phase. Fully ferrite–bainite dual phase steels have been reported to show discontinuous yielding behavior in stress-strain plots.6) The corresponding plots for the present steels (Fig. 4) clearly indicate that they are of continuously yielding type, a behavior normally shown by ferrite–martensite dual phase steels. In the present case the variation of martensite in the different steels ranges between 2.1 to 5.8%. Rigsbee et al.13) have suggested that at least 4% martensite in ferrite–martensite dual phase steels is necessary in order to get the continuous yielding behavior. The present work clearly shows that this can be achieved with even lesser amount of martensite present in a ferrite–bainite dual phase steel. The TEM results have clearly indicated that there is always a high dislocation density in the ferrite regions adjoining martensite (Fig. 3(d)), whereas no significant build-up of dislocations can be seen in the ferrite adjoining bainitic areas. However, there is considerable evidence to indicate that the dislocation density in bainite is higher than that in allotriomorphic ferrite which has formed at a similar transformation temperature.14) Researches carried out by Smith15) and Graf et al.16) also support this find-
ing. Therefore, the requirement of extra mobile dislocations to cause continuous elongation may be less in a ferrite–bainite matrix than in purely ferritic matrix. This could be a plausible explanation why a lower (−2%) volume fraction of the martensite phase in a ferrite–bainite matrix is good enough to produce continuous yielding behavior. This again indicates that in these basically ferrite bainite dual phase steels it is mainly the extra punched in mobile dislocations around the martensite regions which give rise to the observed continuous yielding behavior.

The high amount of Mn in these steels stabilizes the austenite sufficiently and hence retards formation of pearlite. The presence of V, Mo or Cr also causes the retardation of pearlite formation and, therefore, facilitates the formation of a dual phase microstructure, consisting mainly of ferrite and bainite. The presence of the stronger carbide forming elements like V, Mo or Cr in the steels B, C and D may lead to the formation of their carbides in addition to Fe,C in the bainitic regions. Therefore the amount of carbon to diffuse away into the austenite could decrease because it is tied up in the alloy carbide particles.9 This may cause the carbon content in the remaining austenite to go below the level required for the formation of martensite. This may be a possible reason for the formation of lesser amounts of martensite in the steels B, C and D as compared to that in steel A.

A study of the mechanical properties of the four steels (Table 3) clearly indicates that the base steel composition, steel A, has the least yield and ultimate tensile strengths. Steel D, with the richest chemical composition, exhibits the highest yield and ultimate tensile strengths. These strength values for steels B and C are intermediate between those of A and D. The percentage elongation and percentage reduction in area of the first three steels are not much different from one another; however, these values are the least for steel D. Steel A also has the highest YS/UTS value among the four experimental alloys.

The highly ductile nature of the four steels, changes drastically when impact testing is carried out at the low temperature of −40°C. The three steels B, C and D become very brittle in nature, while steel A containing the least amount of solute elements shows the highest impact value at −40°C (see Fig. 6). As has been mentioned earlier, steel B shows the best combination of tensile strength and %elongation, whereas steel D exhibits the best combination of all the three mechanical property parameters—tensile strength, %elongation and charpy impact value. It is interesting to note that both steels B and D contain the minimum amount of martensite volume fraction (−2%) among the four steels.

The differential C-J analysis revealed that the experimental ferrite–bainite dual phase steels deform in two stages. The first stage presumably involves the deformation of the softer ferrite matrix. The slope is less in the first stage for all the four different steels as compared to the second stage when the much harder bainite phase deforms. The negative \( n \) value may be associated with high internal stress due to the high density of lattice defects and/or heterogeneity of microstructure consisting of the ferrite, bainite and martensite phases.8

Umemoto \textit{et al}.\textsuperscript{6} analysed the stress–strain data of several steels having a single phase microstructure in order to understand their strain hardening behavior. This was carried out using all the three techniques such as the differential (C-J), Hollomon or the modified C-J analysis. Their results have shown that ferritic and pearlitic steels as well as steels with as upper bainite microstructure exhibit a two stage work hardening behavior, each stage being associated with a distinct value of the work hardening exponent. On the other hand, according to them, martensitic and lower bainitic microstructures in steels show a single stage work hardening behavior.

The results of the present investigation clearly show a two stage work hardening characteristics in the experimental steels. It may be mentioned here that these steels have basically a dual phase microstructure, consisting of ferrite and bainite, along with just a little bit of martensite. It is no wonder, therefore, that the mechanical behavior of these steels is quite similar to the ferritic and bainitic steels, as reported by Umemoto \textit{et al}..\textsuperscript{9} The values of the strain hardening exponent \( n \) for the experimental steels are not much different from what has been reported by them for single phase ferritic and bainitic steels.

It may be mentioned here that a few ferrite–martensite dual phase steels were subjected to similar kind of analysis by Tomita and Okabayashi.\textsuperscript{10} They also reported a two stage work hardening behavior for these steels; however the calculated \( n \) values for such steels have been found to be much larger than the \( n \)-values for the present ferrite–bainite dual phase steels.

4.2. Ferrite–Bainite Dual Phase Steels

Conventional ferrite–martensite dual phase steels exhibit some typical properties, such as continuous yielding behavior, high value (−0.2) of the work hardening exponent and moderately low values (−0.55−0.65) of YS/UTS ratio. The present series of alloy, hot rolled from austenitic range, consists of three phases: ferrite (between 23 and 51% by volume), bainite (between 47 and 74% by volume) and only very little amount of martensite (between −2 and −6% by volume). In the literature very little has been published on the mechanical behavior of ferrite–bainite dual phase steels, let alone such steels with as high a bainite content as in the present series of alloys.

Mechanical properties, such as YS, UTS and YS/UTS ratio similar to those of the present hot rolled alloys were also obtained by Bodin \textit{et al}..\textsuperscript{11} who studied a few low silicon and microalloyed dual phase steels in the hot rolled condition. These authors claimed that they could achieve typical dual phase microstructures and properties in their steels, using the high coiling temperature option which is very similar to the situation in the present case. Unfortunately, however, these authors did not disclose the phase compositions obtained in their alloys after hot rolling. They have further shown in their paper that a simple ferrite–bainite dual phase structure will not show the typical continuous yielding behavior of conventional ferrite–martensite dual phase steels. Kim \textit{et al}.\textsuperscript{17} have clearly shown that some amount of martensite must be present in a ferrite–bainite dual phase steel in order to achieve the continuous yielding behavior. The present work has also shown clearly that triple phase ferrite–bainite–martensite structures with
even rather small amount of the martensite phase is necessary for imparting the continuous yielding behavior to these steels. It can therefore be presumed that the hot rolled steels, mentioned by Bodin et al. should, in all probability, be containing some martensite in addition to the ferrite and bainite phases. Of course, with the type of alloy compositions mentioned by them and after hot rolling with the high coiling temperature option, it will not be possible to achieve a fully ferrite–martensite structure. The present results clearly demonstrate that hot rolled ferrite–bainite–martensite triple phase steels of 600–700 MPa grade can be produced industrially using existing facilities in steel plants and these will have properties comparable to the conventional ferrite–martensite dual phase steels. Such steels could be considered initially for automotive applications such as wheel discs.

5. Conclusions

(1) Small amount (at least 2% by volume fraction) of martensite is sufficient to produce continuous yielding behavior in ferrite–bainite dual phase steel.

(2) Ferrite–bainite dual phase steels containing very substantial amounts of bainite can achieve high strength coupled with adequate ductility.

(3) Addition of alloying elements such as Cr, Mo or V increases the strength levels of the different phases.

(4) All the four steels show a two stage work hardening behavior, each stage being associated with a distinct value of the work hardening exponent, $n$.

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REFERENCES