Introduction
The microstructure of bainite consists of a non-lamellar mixture of ferrite and carbides, which can be classified further into upper and lower bainite depending on the details of carbide precipitation. In upper bainite the partitioning of carbon from supersaturated ferrite into the residual austenite is so rapid that the cementite precipitates from the austenite, between the ferrite plates; while cementite also forms within the bainitic ferrite plate in lower bainite. Alloying elements can affect the kinetics of cementite precipitation substantially. The purpose of this study is to extend the model developed by Takahashi and Bhadeshia to include the solutes Mn, Si and Cr, and apply the results to a wide variety of steels.

Model construction
• Cementite precipitation
The kinetics of cementite precipitation from bainitic ferrite plate was modelled under paraequilibrium condition, using MatCalc. The time for a cementite fraction of 0.01 of its equilibrium quantity is used to define the start time \( t_\text{p} \). Large amount of data was collected by varying composition and temperature. The base composition was otherwise listed in Table 1.

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Ni</th>
<th>Mo</th>
<th>Cr</th>
<th>Cu</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.224</td>
<td>1.0</td>
<td>1.542</td>
<td>0.086</td>
<td>0.141</td>
<td>1.54</td>
<td>0.168</td>
<td>0.146</td>
</tr>
</tbody>
</table>

The resulting relations between precipitation start times and alloy element contents and temperatures are very complex and non-linear. Neural network method was therefore used to represent the calculated data including alloy composition, temperature and cementite precipitation start time as the variables.

• Decarburisation
The time required to decarburise a supersaturated bainite subunit is given by

\[
t_\text{d} = \frac{\pi n_w^2 (X - x^{\text{eq}})^2}{16D(x^{\text{eq}} - X)^2}
\]

where \( t_\text{d} \) is the decarburising time, \( n_w \) is the thickness of the bainite subunit, \( X \) is the nominal carbon content of the alloy, \( x^{\text{eq}} \) and \( x^{\text{eq}} \) are the carbon content of ferrite and austenite at the interface where they are in paraequilibrium.

Validation
• Fe-C system

![Figure 1](image1.png)

Figure 1 Alloying element and temperature effects on \( t_\text{p} \) for 0.2 C wt% alloy.

![Figure 2](image2.png)

Figure 2 Alloying element and temperature effects on \( t_\text{p} \) for 0.8 C wt% alloy.

![Figure 3](image3.png)

Figure 3 Effects of allolying elements and temperature on decarburisation time.

![Figure 4](image4.png)

Figure 4 Calculated \( t_\text{d} \) and \( t_\text{p} \) for plain carbon steel of 0.1-0.6 C wt%, the solid lines are \( t_\text{d} \), the dash lines are \( t_\text{p} \).

![Figure 5](image5.png)

Figure 5 Calculated \( L_B \) for plain carbon steel.

• Fe-Mn-Mo-C alloys

![Figure 6](image6.png)

Figure 6 Calculated \( L_B \) for Fe-Mn-Mo-C alloy.

• Experimental steel

![Figure 7](image7.png)

Figure 7 Calculated \( t_\text{d} \) and \( t_\text{p} \) for plain carbon steel of 0.1-0.4 C wt%, the solid lines are \( t_\text{d} \), the dash lines are \( t_\text{p} \).

![Figure 8](image8.png)

Figure 8 TEM bright field image of isothermal transformation at 400 °C, 370 °C and 340 °C for 1 h. (a) 400 °C, (b) 370 °C, the inset is the diffraction pattern from the circled area, the carbides was confirmed to be cementite, zone axes are [351] and [361] for blue and red patterns respectively. (c) 340 °C

Conclusion
A model for transition from upper to lower bainite has been developed by comparing the time required for decarburising a supersaturated bainite plate and the time for cementite precipitation within the ferrite plate. Good agreement was achieved for Fe-C system and low alloyed Fe-Mn-Mo-C system, broad agreement was reached for a commercial Si-containing multicomponent steel. The model predicts that C and Mn favour lower bainite, while Si promotes upper bainite.