Stretch–flangeability of Strong Multiphase Steels

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Abstract

Stretch–flangeability measures the ability of a material to be formed into a complex shape. The parameter is often related to simple properties derived from tensile tests. An attempt is made here to discover the best way to exploit tensile test data to represent flangeability. It is found that the ultimate tensile strength of a steel is the single most important criterion that correlates with stretch–flangeability.

1 Introduction

Several methods have been designed to characterise formability, one of which is the hole expansion test which is of relevance in the manufacture of steel automobile components [1–3]. A hole is first made in the steel blank. It is then allowed to expand under a punch until cracks appear on the surface. The ratio of the increase in diameter to the initial diameter is called the hole expansion ratio. The higher the ratio, the better is the stretch–flangeability.

There are examples of strong steels tested for stretch–flangeability [2–7]. Each of these materials possesses a similar ferrite–rich microstructure with a dispersion of a hard phase which could be martensite or bainite or both; retained austenite may also be present. The ideal way of relating microstructure to properties such as the hole expansion ratio would be to create a finite element model for the component which is to be formed, containing as inputs the complete constitutive equations for each phase, the scale, distribution and failure criterion for each phase and a way of creating composite effects in such a model. This scenario is frequently impractical in steel development programmes, where parameters derived from tensile tests are suggested to correlate with the hole expansion ratio.

A recent though common example is the correlation of formability with the ultimate tensile strength (UTS) and ductility, for example, [8]. The argument for doing this is that the product is a measure of the energy absorbed by the steel during uniform plastic deformation. However, the UTS itself contains information about the onset of plastic instability so it is not obvious that information is not double–counted. The purpose of this work was to examine in detail how the tensile test should correlate against the hole expansion ratio.
2 Method

A good method for recognising patterns in complex data is the neural network in a Bayesian framework. The method has been extensively documented [9–12] and applied in materials science [13–23]. For this reason only specific points of relevance are introduced here – details are available in a recent thesis [24].

The network is a non-linear regression method which, because of its flexibility, is able to capture enormous complexity in the data, whilst at the same time avoiding overfitting. There are a number of interesting outputs other than the coefficients which help recognise the significance of each input. First, there is the *noise* in the output, associated with the fact the input set is unlikely to be comprehensive – i.e., a different result is obtained from identical experiments. Secondly, there is the *uncertainty of modelling* because many mathematical functions may be able to adequately represent known data but which behave differently when extrapolated. A knowledge of this uncertainty helps make the method less dangerous in extrapolation. Finally, there is the *significance* of each input in explaining variation in the output, akin to a partial correlation coefficient in multiple linear regression. Note that the significance is dimensionless because the variables are all normalised between 0.5 and 1 for the purposes of creating the neural network model (*e.g.*, equation 2, [15]).

3 Data

The data presented in Table 1 were compiled from published literature [1, 2, 4, 25, 26]. They originate from steels with microstructures which are mixtures of ferrite and martensite, or ferrite and bainite, with or without retained austenite. The data were used to create models for predicting the hole expansion ratio ($\lambda$) against various combinations of the tensile properties *viz.* yield strength (YS), ultimate tensile strength (UTS), uniform elongation (UEL), total elongation (TEL), yield ratio (YR) and the strength-elongation product (UTS-UEL and UTS-TEL).

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Average</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>YS / MPa</td>
<td>335</td>
<td>783</td>
<td>444</td>
<td>92</td>
</tr>
<tr>
<td>UTS / MPa</td>
<td>484</td>
<td>1028</td>
<td>675</td>
<td>155</td>
</tr>
<tr>
<td>UEL / %</td>
<td>8</td>
<td>39</td>
<td>18</td>
<td>7</td>
</tr>
<tr>
<td>TEL / %</td>
<td>10</td>
<td>43</td>
<td>27</td>
<td>8</td>
</tr>
<tr>
<td>YR</td>
<td>0.49</td>
<td>0.82</td>
<td>0.67</td>
<td>0.09</td>
</tr>
<tr>
<td>UTS-UEL / MPa-%</td>
<td>6992</td>
<td>29715</td>
<td>12192</td>
<td>6113</td>
</tr>
<tr>
<td>UTS-TEL / MPa-%</td>
<td>9016</td>
<td>32379</td>
<td>18069</td>
<td>6894</td>
</tr>
<tr>
<td>$\lambda$ / %</td>
<td>9</td>
<td>151</td>
<td>65</td>
<td>45</td>
</tr>
</tbody>
</table>

Table 1: Data used in the analysis.

4 Results and discussion

The first model included YS, UTS, UEL, YR and UTS–UEL as the inputs with the hole expansion ratio $\lambda$ as the output. Fig. 1a shows how well the model compares with the experimental data. There are a number of outliers and the modelling uncertainty is large. However, the interesting outcome seen in Fig. 1b is that neither the uniform elongation (UEL) nor the product of the ultimate tensile strength with it (UTS–UEL) are perceived to be significant when compared with strength.
Figure 1: (a) Predicted hole expansion ratios compared with the measured values using the model with YS, UTS, YR and UTS–UEL as the input parameters. (b) Significance of each input.

The apparent lack of relevance of the uniform elongation was further tested, first by using only the UTS with the UEL as the inputs and secondly with only YS and UEL as inputs. Fig. 2 shows that in the first case, the UTS has an overwhelming contribution with the uniform elongation having a negligible influence on \( \lambda \). When the yield strength is substituted for the UTS, the significance of the uniform elongation increases only slightly.

![Figure 2](image)

Figure 2: Significant of (a) UTS and UEL and (b) YS and UEL as the input variables.

Repeating this exercise using UTS, TEL and UTS-TEL led to the most interesting results and the least noise in the predictions. From Figure 3a,b, the significances of both UTS-TEL and TEL can be seen to be appreciable, although quantitatively these are less than that of the UTS. Figure 3c,d shows that the predictions made over the entire dataset compare well with the corresponding measured values. The role of the total elongation appears to be physically reasonable, given that the hole must be allowed to expand until cracks appear on the surface.

![Figure 3](image)

Figure 3: (a) UTS and TEL used as the input variables, and (b) UTS-TEL used as the input variables. (c) Predictions compared with the corresponding measured values using UTS and TEL as the input variables. (d) Predictions compared with the corresponding measured values using UTS and TEL as the input variables.

Given that both of the models illustrated in Fig. 3 include significant variables and that the accuracies of the predictions are comparable, it would be better to select the model in which the inputs are independent, i.e., the UTS and TEL model. Figure 4 shows that the ultimate tensile strength has a powerful effect on the hole expansion ratio, more so than the total elongation.

![Figure 4](image)

Figure 4: (a) Comparison of predicted and measured hole expansion ratios using the model with UTS and TEL as the input parameters. (b) Comparison of predicted and measured hole expansion ratios using the model with UTS–UEL as the input parameters.

That the ultimate tensile strength has such a large effect on \( \lambda \) should not be surprising in hindsight. First, the ultimate tensile strength is measured at the point where plastic instability sets in, and hence already contains information about uniform elongation. Secondly, it is generally true in the type of steels considered here that a higher ultimate tensile strength leads to a lower uniform elongation.
Figure 3: Significances of (a) UTS and UTS-TEL and (b) UTS and TEL as the input variables. Predicted hole expansion ratios compared with the measured values using the models with (a) UTS and UTS-TEL and (b) UTS and TEL as the input parameters.

Figure 4: Predicted variation in (a) the hole expansion ratio with UTS and TEL and (b) the corresponding uncertainties.
Finally, it is worth noting that the correlation of the hole expansion ratio versus the popular product $UTS \times TEL$ is not impressive. Fig. 5 shows the performance of a neural network model for $\lambda$ as the output with only the product as the input.

![Graph showing performance of a neural network](image)

Figure 5: Performance of a neural network containing just the product $UTS \times TEL$ as the input.

5 Conclusions

It is found that the ultimate tensile strength is of overwhelming importance in determining the hole expansion ratio, and hence the stretch-flangeability. In contrast, the uniform elongation should not be used in analysing the ratio. The total elongation is a significant parameter but the ratio $\lambda$ is less sensitive to this than the UTS. It does not appear justified to expect a correlation between the hole expansion ratio and the product of strength and total elongation.

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References


