EFFECT OF TEMPERING TREATMENT ON FRACTURE TOUGHNESS
OF 0.4 C STEEL

I.B. Eryürek* E.Akata**

JR and R curves of 0.4 C quenched and tempered steel have been obtained using Charpy-sized, %20 side-grooved specimens with LT orientation.

J values are found not to be dependent on the yield strength. Resistance to crack initiation and stable crack growth characterized with $d_1$ and $d_6/da$ and $d_3/da$ respectively are found to vary with the yield strength. These variations are empirically related to the carbide spacing.

INTRODUCTION

The ductile fracture of medium and high carbon steels containing a significant volume fraction of carbide particles follows a dual scale process of void nucleation and coalescence. Large voids formed at nonmetallic inclusions subsequently link through the formation of finer secondary voids at carbide particles (Stone and Cox (1), Curry and Pratt (2)).

The object of this study was to examine the effect of carbide particle spacing on the crack initiation and propagation behaviors of quenched and tempered 0.4 C steel.

EXPERIMENTAL PROCEDURE

The chemical composition of the steel used in this study is given in Table 1. All specimens were normalised at 870°C. Then, they were austenitized at 870°C and water quenched and subsequently subjected to tempering treatment at different temperatures, namely, 600°C, 525°C, 450°C, 350°C, for two hours. One group of specimens was spheroidized by furnace cooling from austenite range to 700°C and held at this temperature for 40 h. Mechanical properties of the specimens after heat treatment are given in Table 2.

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TABLE 1- Chemical composition of the steel (weight %).

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>S</th>
<th>P</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>Sn</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.36</td>
<td>0.22</td>
<td>0.9</td>
<td>0.027</td>
<td>0.028</td>
<td>0.08</td>
<td>0.14</td>
<td>0.02</td>
<td>0.02</td>
<td>0.004</td>
</tr>
</tbody>
</table>

TABLE 2- Mechanical properties of the specimens.

<table>
<thead>
<tr>
<th>Tempering Temperature (°C)</th>
<th>Yield Strength $\sigma_{ys}$ (MPa)</th>
<th>Tensile Strength $\sigma_{ts}$ (MPa)</th>
<th>Elogation (%)</th>
<th>Reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spher.</td>
<td>500</td>
<td>624</td>
<td>32</td>
<td>59</td>
</tr>
<tr>
<td>600</td>
<td>690</td>
<td>786</td>
<td>26</td>
<td>55</td>
</tr>
<tr>
<td>525</td>
<td>866</td>
<td>957</td>
<td>22</td>
<td>48</td>
</tr>
<tr>
<td>450</td>
<td>1015</td>
<td>1085</td>
<td>1.6</td>
<td>1.6</td>
</tr>
<tr>
<td>350</td>
<td>1220*</td>
<td>675</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

* Obtained from compression test

Precracked Charpy-type three point bend test pieces with LT orientation were used. They had 1 mm side grooves to eliminate shear lips. The resistance to crack initiation and crack propagation were characterized in terms of $\delta_i(J_i)$ and $d\delta/da (dJ/da)$ respectively. $\delta$ values were calculated according to the procedure given in BS 5762. $J$ values were estimated by applying the formula (Rice et al. (3)):

$$ J = 2U/BN(W-a_0) $$

where $U$ is the area under the load-deflection curve, BN net thickness (8 mm), W width (10 mm) and $a_0$ original crack size (4-6 mm).

The yield strength of a quenched and tempered steel had been shown to vary linearly with the reciprocal square root of the carbide spacing (Lui and Gurland (4), (2)). For this reason, the yield strength was taken as a parameter representing the carbide spacing.

RESULTS AND DISCUSSION

Figures 1 and 2 show the dependence of $\delta R$ and $JR$ curves on the yield strength. The values $\delta_i(J_i)$ and $d\delta/da (dJ/da)$ obtained from Figures 1 and 2 are given in Table 3.
TABLE 3- Effect of yield strength (σYS) on δi(Ji) and dδ/da(dJ/da) values.

<table>
<thead>
<tr>
<th>σYS (MPa)</th>
<th>δi (µm)</th>
<th>Ji (kJ/m²)</th>
<th>dδ/da (-)</th>
<th>dJ/da (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>45</td>
<td>30</td>
<td>0.54</td>
<td>500</td>
</tr>
<tr>
<td>690</td>
<td>32</td>
<td>30</td>
<td>0.27</td>
<td>350</td>
</tr>
<tr>
<td>866</td>
<td>25</td>
<td>30</td>
<td>0.15</td>
<td>260</td>
</tr>
<tr>
<td>1015</td>
<td>20</td>
<td>30</td>
<td>0.09</td>
<td>200</td>
</tr>
<tr>
<td>1220</td>
<td>18</td>
<td>30</td>
<td>0.02</td>
<td>13</td>
</tr>
</tbody>
</table>

The specimens with the yield strength below 1220 MPa were found to satisfy the following conditions for specimen dimention (ASTM E 318) and J-controlled crack growth (shih et al (5):

\[ a_0, (W-a_0), B_N > 25J_i \sigma_{YS} \]

\[(dJ/da)/\sigma_{YS} > 0.1\]

Ji values were found not to be dependent on the yield strength as reported by Curry and Pratt (2). On the other hand, δi values were found to be strongly dependent on the yield strength as shown in Figure 3. Figure 3 shows that the relationship,

\[ \delta_i = 22000 \sigma_{YS} \]

exists between δi and σYS where δi is in (µm) and σYS in (MPa). This relationship also proves the constancy of Ji values, since,

\[ J_i \propto \sigma_{YS} \delta_i \]

As the yield strength of a quenched and tempered steel varies linearly with the reciprocal square root of the carbide spacing (2), equation (4) also suggests that δi varies linearly with the square root of the carbide spacing, D. This result also agrees with the relationship given by Curry and Pratt (2):

\[ \delta_i \propto X_0 D^{1/2} \]

where X0 is the inclusion spacing which is constant for all specimens used in the present study.

Figure 4 shows the relationship between the non-dimensional slope of JR curve and the slope of δR curve. Figure 4 suggests that the relationship,

\[(dJ/da)/\sigma_{YS} = 1.87 (dδ/da)\]
exists between the slopes. The data in Table 3 also suggests the following relationships:

\[ d\delta/da = 2.63 \times 10^{-4} \delta_i^2 \]
\[ dJ/da = 10.8 \delta_i \]

where \( \delta_i \) is in (\( \mu \)m) and \( dJ/da \) in (MPa). From equations (6), (8) and (9) it can be concluded that the slopes of \( \delta R \) and \( JR \) curves vary linearly with carbide spacing and with the square root of carbide spacing, respectively.

**ADDITIONAL SYMBOLS**

- \( d\delta/da \) = initial slope of \( \delta R \) curve
- \( dJ/da \) = initial slope of \( JR \) curve (MPa)
- \( D \) = carbide spacing (\( \mu \)m)
- \( U \) = area under load-deflection curve (kJ)
- \( X_0 \) = inclusion spacing (\( \mu \)m)

**REFERENCES**

(1) Stone, R.H. and Cox, T.B., ASTM, STP 600, 1975, pp.5-13.
Figure 1 Effect of yield strength on $\delta_R$ curves.

Figure 2 Effect of yield strength on $J_R$ curves.

Figure 3 Variation of $\delta_i$ with the reciprocal of $\sigma_{YS}$.

Figure 4 Variation of $\sigma_{YS}(dj/da)$ with $d\delta/da$. 

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