INFLUENCE OF STRESS CONCENTRATORS ON THE TEMPERATURE DEPENDENCE OF THE LIQUID METAL EMBRITTLEMENT OF ARMCO IRON

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We study temperature dependences of the effects of liquid indium and lead-bismuth eutectics on the ultimate strength and tensile elongation of Armco iron. Tests were performed on Armco iron cylindrical specimens with stress concentrators and with square cross section under active strain with a rate of $8.3 \times 10^{-4}$ s$^{-1}$. It was found that, under identical test conditions, the decrease in the ultimate strength of the specimens with concentrators caused by the effect of melts occurs in a broader temperature range than the embrittlement of specimens without concentrators. The effect of liquid metal also depends on the size of the grains in iron ($26 - 110 \mu m$) but its character is different for specimens with and without concentrators.

At present, it is an established fact that liquid metal embrittlement (LME) of steels by adsorbing melts occurs within a limited temperature range [1-5] closely connected with the temperature range of dynamic strain aging (DSA) [1, 6, 7]. The lower temperature of the ductile–brittle transition lies in the temperature range where the plasticity of steel takes its minimal value as a result of DSA and does not necessarily coincide with the melting point of embrittling metal [5, 6]. (In this paper, transition temperatures are defined as the points where the fracture type changes. Thus, the lower temperature of the ductile–brittle transition is the temperature at which fracture caused by the melt originates from the surface cracks; at the upper temperature, fracturing in the melt is again of the ductile type.)

By investigating the temperature range of Armco iron embrittlement on plain cylindrical specimens, it was discovered [8] that the lower temperature of the ductile–brittle transition in different adsorbing melts depends on the same factors as the upper temperature (structure and strain rate). At the same time, it is different for different melts while the upper temperature remains practically independent of the melt [8].

**Thermal Treatment of Specimens to Obtain Grains of Different Size**

<table>
<thead>
<tr>
<th>Batch of specimens</th>
<th>Annealing temperature, °C</th>
<th>Annealing time, h</th>
<th>Average diameter of grains, µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>500</td>
<td>1</td>
<td>26</td>
</tr>
<tr>
<td>2</td>
<td>1100</td>
<td>2</td>
<td>80</td>
</tr>
<tr>
<td>3</td>
<td>1250</td>
<td>5</td>
<td>110</td>
</tr>
</tbody>
</table>

The results of the investigation of LME of St3sp steel on small specimens with rectangular cross sections of $1 \times 3$ mm appear to be somewhat different from the data obtained on cylindrical specimens [3]. The temperature range of embrittlement is very narrow in this case and shifted toward temperatures close to the upper limit of steel DSA.

These data indicate that the temperature range of embrittlement may depend on the shape of the specimens. The existence of such a dependence would be additional corroboration of our phenomenological model of LME proposed in [7] since the shape is responsible for the stressed state of some parts of the specimen and, hence, affects the process of local plastic deformation, which, in turn, may change the effect of the medium.


Influence of Stress Concentrators on the Temperature Dependence of Liquid Metal Embrittlement

Fig. 1. Temperature dependence of the ultimate strength of Armco iron specimens with stress concentrators in vacuum (1), in Pb–Bi eutectic melt (2), in indium melt (3).

In this work, we study the LME temperature range as a function of stress concentration caused by the specially designed shape of the working part of the specimens.

The experiments were carried out on the cylindrical specimens made of Armco iron (0.037 wt. % carbon) with a diameter of 9 mm. Stress concentrators with a depth of 0.75 mm were notched in the specimens with a polishing wheel (with an expansion angle of 60° and a curvature radius of 0.1 mm). In some specimens, the cross section was made in the form of a 6×6 mm square. This was achieved by polishing the lateral surfaces of cylindrical specimens. After preparation, the specimens with stress concentrators were annealed at certain experimentally determined temperatures for different periods of time to obtain grains of the necessary sizes (see Table 1).

Specimens with square cross sections were annealed at 1100°C for 2 h; the average size of the grains in these specimens was 80 μm.

After preparation and thermal treatment, some of the specimens with stress concentrators and with square cross section were tested in 1.3-mPa vacuum; the remaining ones were coated by fluxing with the corresponding melts. We took special care to guarantee that the concentrators would be wetted by the melt. The specimens were tested under active tension on an MP-41 device in the vacuum chamber at a strain rate of 8.3·10⁻⁴ s⁻¹. The specimens coated with eutectic Pb–Bi melt film were tested in trays filled with the same melt that was also protected with vacuum. The specimens covered with indium were strained together with the applied films because, as was shown earlier [8], the data obtained in a vacuum of 1.3 mPa for the case where the specimens were just covered with indium films coincide with the results obtained for the specimens kept in the trays filled with indium. The influence of melts was estimated by analyzing either ultimate strength σ_u (for the specimens with stress concentrators) or both ultimate strength and relative elongation δ (for the specimens with square cross section).

The results of testing the specimens with stress concentrators and a grain size of 80 μm in vacuum (Fig. 1, curve 1) indicate that, as the temperature increases from 100 to 350°C, the strength of the specimens also rises in view of DSA. At temperatures higher than 350°C, ultimate strength is an almost linearly decreasing function of temperature. The influence of the melts manifests itself at lower temperatures than in the case of plain specimens (where it was estimated by using the parameter δ) at the same strain rate. Unlike the plain specimens, where the embrittling effect of indium melt was not observed at 200°C (for Pb–Bi eutectic, it was not observed at 250°C [1]), the specimens with stress concentrators exhibit a considerable decrease in strength at 250°C in both melts due to embrittlement. Moreover, one observes a certain decrease in the value of ultimate strength at temperatures lower than the melting point of indium; at the same time, liquid Pb–Bi eutectic does not induce any decrease in the strength of the specimens with stress concentrators practically up to 200°C. This confirms once again that the tendency to liquid metal embrittlement is a consequence of the properties of the strained metals and the test conditions but not of the melting temperature of the embrittling metal.