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Effect of temperature on the lower yield strength and static strain ageing in low-carbon steels

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Three different low-carbon steels, namely ASTM 516 Gr70 PVQ, CSA G40.21 350 WT and CSA G40.21 350 AT plates, were tensile tested at temperatures from ambient to 623 K over a range of strain rates ($1.48 \times 10^{-5} - 1.48 \times 10^{-3}\ s^{-1}$). The lower yield strength generally decreases with increasing temperature, but there is a strength plateau, or a small peak, at temperatures between 423 and 573 K. The results of computer modelling show that concentration of nitrogen in the atmospheres at dislocations decreases with increasing temperature, approaches a minimum value at a temperature around 423 K, then increases with increasing temperature for temperatures above 423 K. This effect of temperature on the concentration of nitrogen in atmospheres at dislocations results in the strength plateau or small peak.

1. Introduction

Strain ageing is caused by the interaction between mobile dislocations and solute atoms. These solute atoms of record are mainly carbon and nitrogen in steels because of their high diffusivity [1–3]. A number of researchers believe that at relatively low temperatures, strain ageing is mainly caused by nitrogen rather than carbon because of the much higher solubility of nitrogen than carbon in α-iron [4, 5].

When carbon and nitrogen atoms diffuse to dislocations in the stress field of the dislocations and form "atmospheres" around them, these "atmospheres" will lock the mobile dislocations. This immobility of the dislocations will then result in a higher strength and a lower ductility in steels. The atmospheres can form either before straining, after prestraining and unloading, or during straining. Depending whether the straining and ageing processes take place sequentially or simultaneously, strain ageing can be classified into two groups: static strain ageing (SSA) and dynamic strain ageing (DSA) [6, 7].

DSA and SSA have different effects on the mechanical properties of materials. Generally, DSA affects the plastic deformation or work-hardening behaviour, while SSA affects the yield strength of materials. The focus of many studies of SSA has been the reappearance of the lower yield point upon ageing after prestraining and unloading, and this phenomenon is considered to be a universal manifestation of SSA [8–10]. In addition to the reappearance of the lower yield point upon reloading after prestrain, unloading and ageing, SSA also affects the initial yield strength, but relatively little attention has been paid to this effect and the mechanisms responsible for the observed increase in the yield strength.

In the present research, the effect of SSA on the lower yield strength was investigated experimentally for three grades of steel plate, and then computer modelling was carried out in order to account for some of the experimental results and to gain some insights into the mechanisms involved in the process of SSA.

2. Experimental procedure

2.1. Materials

The materials under investigation were three low-carbon steel plates: one pressure-vessel quality steel plate, ASTM 516 Gr70 PVQ and two construction-grade steel plates, CSA G40.21 350 WT and CSA G40.21 350 AT. They were produced in a fine-grain condition using fully killed steel-making practice. The as-received materials were hot rolled. The chemical composition of the three steels are given in Table I. Typical optical micrographs of the three steels are given in Fig. 1. The microstructure of all three materials consists of ferrite and pearlite. The grain size of material B is slightly finer than the other two materials.

2.2. Specimens

Strips were cut from the plates in the rolling direction and then machined into tensile specimens of 57.15 mm (2.25 in) gauge length and 6.35 mm (0.25 in) cross-sectional diameter.

2.3. Tensile tests

A floor model TT Instron Tensile Test Machine was used for the tensile testing. A Marshal high temperature furnace fitted to the machine was used to heat the specimens. A chromel–alumel thermocouple attached to the middle of the specimen was used for temperature measurement and temperature control.

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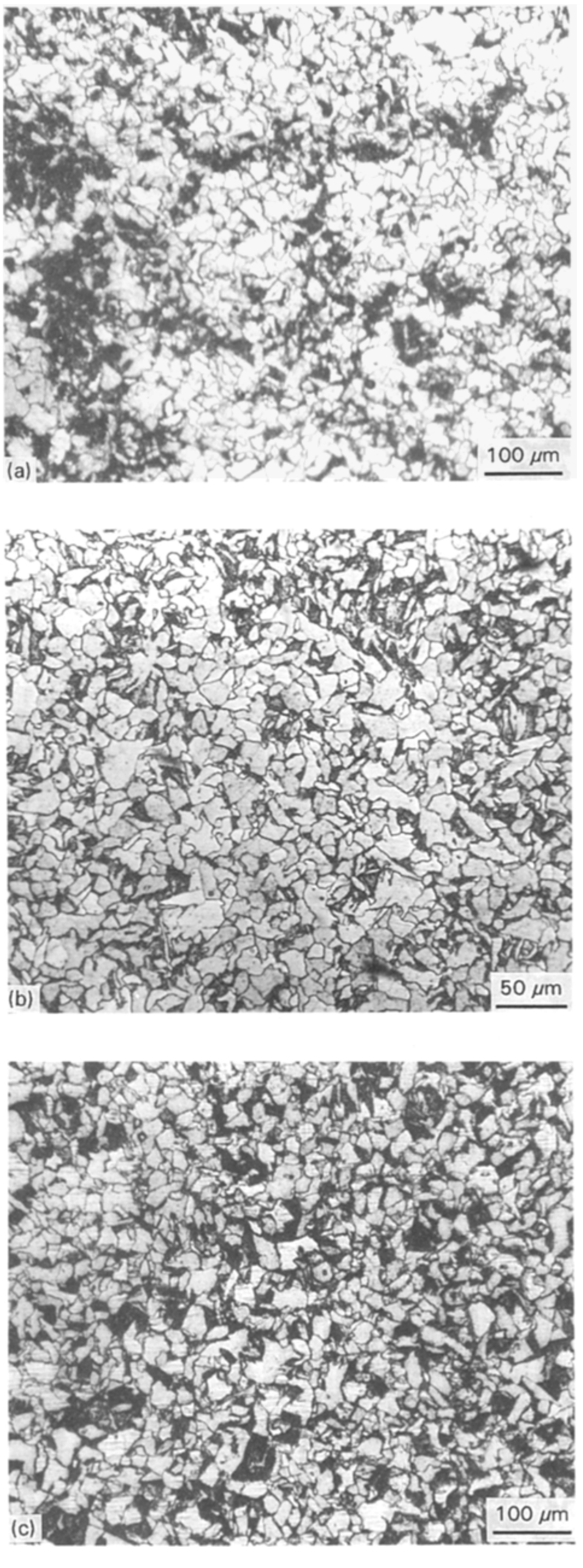

Figure 1 Optical micrographs of steels. (a) Steel A, PVQ steel; (b) steel B, 350 WT steel; (c) steel C, 350 AT steel.

The temperature control was within ± 3 °C. A series of temperatures and strain rates were chosen for the experiments. The temperatures investigated were 293 K (ambient), 373, 423, 473, 523, 573 and 623 K. The strain rates chosen were 1.48×10^{-5}, 7.41×10^{-5}, 3.71×10^{-4} and $1.48 \times 10^{-3}\,s^{-1}$. Three or four specimens were tested under each temperature–strain rate condition and an average value was calculated for each temperature–strain rate–steel combination.

3. Results and discussion

As shown in Fig. 2, the yield strength of the three materials generally decreases with increase in temperature. However, there is a plateau or a small peak in each yield strength versus temperature curve at temperatures between 423 and 573 K. Also from Fig. 2 it can be seen that there is generally a positive strain-rate dependence of the lower yield strength, i.e. the strength increases with increase in strain rate.

Li and Leslie [11] obtained similar results in their studies of two different steels, AISI 1008 and 1035. They found that the lower yield strength decreased with increasing temperature, but in the temperature range between 423 and 473 K, where there were serrations in the stress–strain curve, the rate of decrease in the yield strength with temperature was slower.

It is believed that SSA causes the plateau in the yield strength versus temperature plot, but a question arises as to how SSA causes this plateau, i.e. what are the mechanisms giving rise to the phenomenon. It seems there are three possible answers: (i) enhanced diffusivity of carbon and nitrogen, (ii) higher solubility of the solute atoms, (iii) a higher concentration of solute atoms in atmospheres at dislocations in α-iron at high temperatures, because the yield strength depends on the locking strength of the solute atmosphere and the locking strength depends on the concentration of solute atoms at dislocations, which is affected by the diffusivity of solute atoms and the concentration of solute atoms in the solid solution.

It is generally recognized that, after a specimen is prestrained and unloaded, ageing can take place at temperatures at or above room temperature. The higher the temperature at which the unloaded specimen is kept, the shorter is the time needed to make the lower yield point reappear upon reloading because of the diffusivity of solute atoms. However, the diffusivity of solute atoms does not affect the initial yielding, because all dislocations are satiated with interstitial solute atoms before testing.

In addition, the higher the temperature, the higher is the solubility of carbon and nitrogen in α-iron, and

TABLE I Chemical composition of the materials (wt %)

	Grade	C	Mn	S	P	Si	Cr	Ni	Cu	Mo	Al	V	N
A	A516 Gr70 PVQ	0.21	1.07	0.01	0.011	0.20	0.02	0.01	0.01	0.01	0.039	–	0.0082
B	G40.21 350 WT	0.187	1.20	0.01	0.006	0.17	0.02	0.02	0.06	< 0.01	0.039	< 0.01	0.0042
C	G40.21 350 AT	0.12	1.12	0.009	0.007	0.22	0.42	0.37	0.27	0.001	0.039	0.046	0.0059

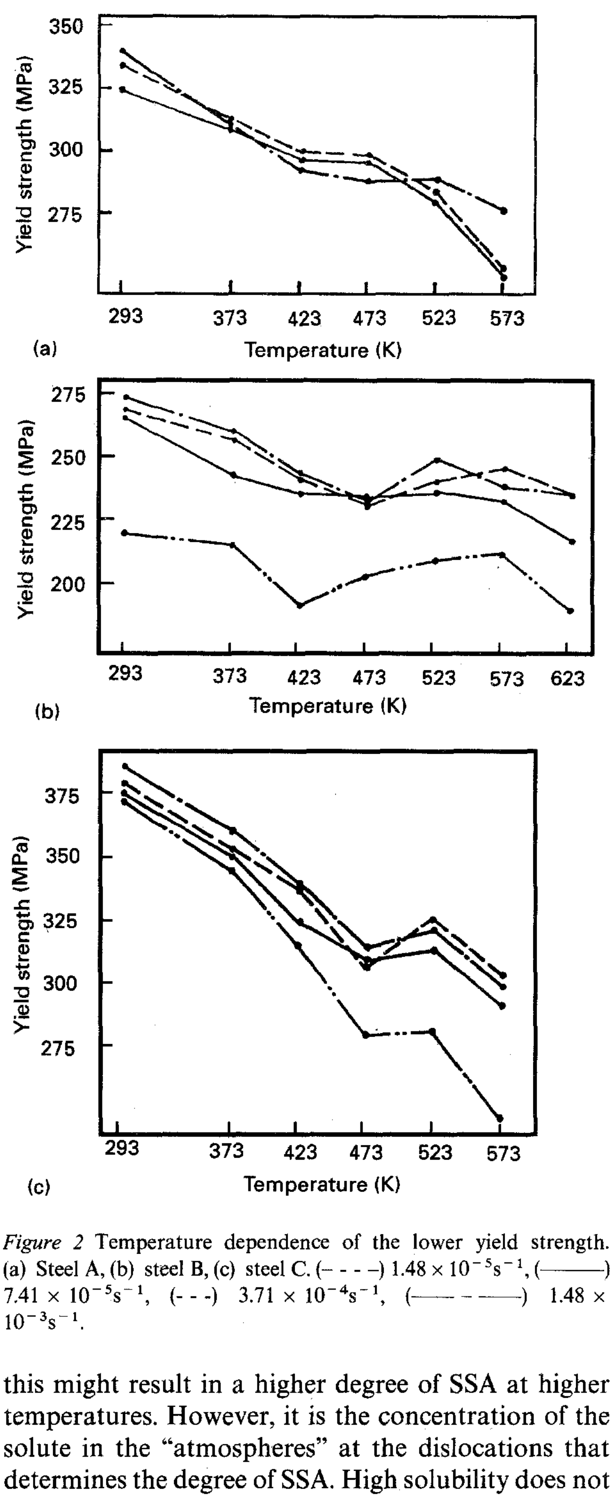

Figure 2 Temperature dependence of the lower yield strength. (a) Steel A, (b) steel B, (c) steel C. (– - - –) 1.48 × $10^{-5}s^{-1}$, (———) 7.41 × $10^{-5}s^{-1}$, (- - -) 3.71 × $10^{-4}s^{-1}$, (——-——) 1.48 × $10^{-3}s^{-1}$.

this might result in a higher degree of SSA at higher temperatures. However, it is the concentration of the solute in the "atmospheres" at the dislocations that determines the degree of SSA. High solubility does not necessarily mean a higher concentration of solutes in the "atmospheres" at dislocations. In fact, sometimes, the concentration of solute in the "atmospheres" can be lower at higher temperatures [12]. Therefore, we cannot necessarily account for the stress plateau by the higher solubility of the solute atoms in α-iron at higher temperatures. We must, therefore, look to the effects of temperature on the solute concentration in the atmosphere of dislocations. This we do in the next section using computer modelling.

4. Computer modelling of the solute concentration at dislocations

According to Li *et al.*'s analysis [13], the increase in free energy by putting a solute atom in a stress field of a solid solution is

$$\Delta G = \Delta G^0 - \sigma\Delta V \qquad (1)$$

where σ is stress, ΔG^0 is the increase in free energy by putting a solute atom into a stress-free region of solid solution, and ΔV is the increase in volume generated by putting a solute atom into the solid solution. Suppose the distribution of solute atoms follows the Maxwell–Boltzmann equation, then the concentration, C, of solute atoms in the stress field, is a function of stress

$$C = C_0 \exp(\sigma\Delta V/kT) \qquad (2)$$

where C_0 is the concentration when $\sigma = 0$.

Now let us consider the stress field of a mixed dislocation in the [0 1 1] direction in a b c c crystal with Burgers vector $(a/2)$ [1 1 1]. As shown in Fig. 3, the orientation of this dislocation is approximately half-way between an edge dislocation [$\bar{2}$ 1 1] and a screw dislocation [1 1 1]. The edge component of the Burgers vector, $\boldsymbol{b}_e$, is $(a/2)$[1 0 0] and the screw component, $\boldsymbol{b}_s$, is $(a/2)$[0 1 1]. In the right-hand coordinate system with x_1[1 0 0], x_2[0 1 $\bar{1}$] and x_3[0 1 1], as shown in Fig. 4, the stress field at a distance r from the

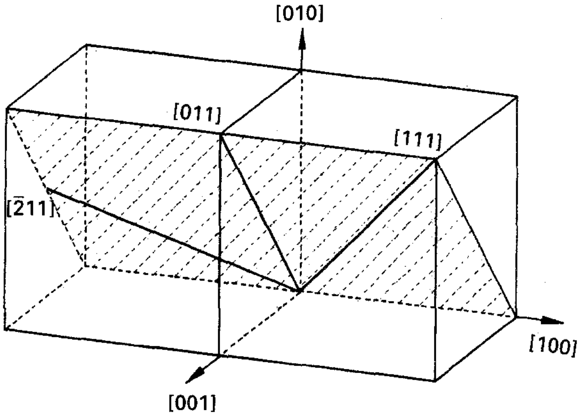

Figure 3 [0 1 1] Dislocation in the b c c lattice.

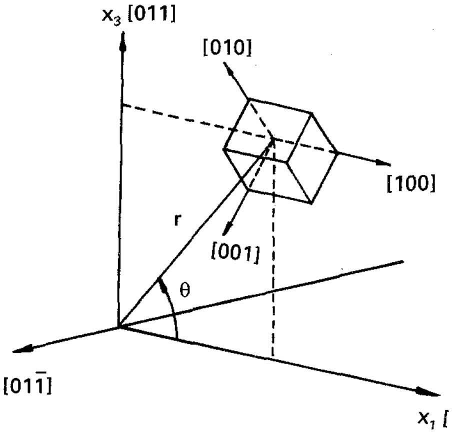

Figure 4 Schematic diagram showing the x_1, x_2, x_3 coordinate system relative to [0 1 1] dislocations.

dislocation has the following components

$$\sigma_{ij} = \frac{Gb_e}{2\pi(1-\nu)r}\begin{vmatrix} -\sin\theta(2+\cos\theta) & \cos\theta\cos 2\theta & -\eta\sin\theta \\ \cos\theta\cos 2\theta & \sin\theta\cos 2\theta & \eta\cos\theta \\ -\eta\sin\theta & \eta\cos\theta & -2\nu\sin\theta \end{vmatrix} \quad (3)$$

where G is the shear modulus, ν is the Poisson ratio, θ is the angle between r and x_1, and $\eta = b_s(1-\nu)/b_e$.

An interstitial atom can occupy either the $(a/2)[1\,0\,0]$, $(a/2)[0\,1\,0]$ or $(a/2)[0\,0\,1]$ positions. If the atom occupies the $(a/2)[1\,0\,0]$ position, the deformation in the $[1\,0\,0]$ direction is referred to as ε_1, and the deformations in the $[0\,1\,1]$ and $[0\,1\,\bar{1}]$ directions are identical and referred to as ε_2; if the atom occupies the $(a/2)[0\,1\,0]$ position, the deformation in the $[0\,1\,0]$ direction is ε_1, and the deformations in the $[1\,0\,1]$ and $[1\,0\,\bar{1}]$ directions are identical and equal to ε_2; if the atom occupies the $(a/2)[0\,0\,1]$ position, the deformation in the $[0\,0\,1]$ direction is ε_1, and the deformations in the $[1\,1\,0]$ and $[1\,\bar{1}\,0]$ direction are identical and equal to ε_2. The strain components in the x_1, x_2 and x_3 system are

$$\varepsilon_{[1\,0\,0]} = \begin{vmatrix} \varepsilon_1 & 0 & 0 \\ 0 & \varepsilon_2 & 0 \\ 0 & 0 & \varepsilon_2 \end{vmatrix} \quad (4a)$$

$$\varepsilon_{[0\,1\,0]} = \begin{vmatrix} \varepsilon_2 & 0 & 0 \\ 0 & (\varepsilon_1+\varepsilon_2)/2 & (\varepsilon_1-\varepsilon_2)/2 \\ 0 & (\varepsilon_1-\varepsilon_2)/2 & (\varepsilon_1+\varepsilon_2)/2 \end{vmatrix} \quad (4b)$$

$$\varepsilon_{[0\,0\,1]} = \begin{vmatrix} \varepsilon_2 & 0 & 0 \\ 0 & (\varepsilon_1+\varepsilon_2)/2 & (\varepsilon_1-\varepsilon_2)/2 \\ 0 & (\varepsilon_1-\varepsilon_2)/2 & (\varepsilon_1+\varepsilon_2)/2 \end{vmatrix} \quad (4c)$$

In the case of nitrogen in α-iron, $\varepsilon_2 = 0$ and $\varepsilon_1 V = \Delta V$, where V is the volume of a unit crystal of α-iron. The increase in free energy by putting a nitrogen atom in the three different positions is, respectively

$$\begin{aligned} \Delta G_{[1\,0\,0]} &= \Delta G^0 + 2\zeta\sin\theta(2+\cos 2\theta)/r \\ \Delta G_{[0\,1\,0]} &= \Delta G^0 - \zeta[\sin\theta(\cos 2\theta - 2\nu) + 2\eta\cos\theta]/r \\ \Delta G_{[0\,0\,1]} &= \Delta G^0 - \zeta[\sin\theta(\cos 2\theta - 2\nu) - 2\eta\cos\theta]/r \end{aligned} \quad (5)$$

where $\zeta = Gb_e\Delta V/4\pi(1-\nu)$. The average concentration, $\bar{C}$, in a cylinder from r_0 to r_1 around the $[0\,1\,1]$ dislocation can be calculated from

$$\begin{aligned} \bar{C} = {} & \frac{C_0}{3\pi(r_1^2 - r_0^2)} \\ & \times \left\{ \int_0^{2\pi}\int_{r_0}^{r_1} e^{-2(\zeta/kT)\sin\theta(2+\cos 2\theta)/r}\, r\mathrm{d}r\mathrm{d}\theta \right. \\ & + \int_0^{2\pi}\int_{r_0}^{r_1} e^{(\zeta/kT)[\sin\theta(\cos 2\theta - 2\nu) + 2\eta\cos\theta]/r}\, r\mathrm{d}r\mathrm{d}\theta \\ & \left. + \int_0^{2\pi}\int_{r_0}^{r_1} e^{(\zeta/kT)[\sin\theta(\cos 2\theta - 2\nu) - 2\eta\cos\theta]/r}\, r\mathrm{d}r\mathrm{d}\theta \right\} \end{aligned} \quad (6)$$

Consider $G = 82\,000\ \mathrm{MN\,m^{-2}}$ at 273 K, and that G decreases 3.5% when the temperature increases by 100 K [14], $r_0 = 3\times 10^{-10}$ m and $r_1 = 1.5\times 10^{-7}$ m, and $\bar{V} = 5.9\ \mathrm{cm^3/g.at}\ N$ ($\bar{V}$ is the partial volume of nitrogen in α-iron) [12]. We can also calculate the solubility of nitrogen in undeformed α-iron using the following equation [15]

$$C_N(\mathrm{wt}\,\%) = 12.3\exp(-34.7(kJ\,\mathrm{mol}^{-1})/RT) \quad (7)$$

$C_0 = C_N$ because C_0 is the solubility of nitrogen in the stress-free area. Introducing these values into Equation 6, we obtain the results of the computations that are summarized in Table II. These data are plotted as $\bar{C}$ versus temperature in Fig. 5a, which shows that the concentration of nitrogen at dislocations decreases with increasing temperature (in region I) and approaches a minimum value at around 423 K. At temperatures above 423 K, $\bar{C}$ increases rapidly at first (in region II), then increases at a decreasing rate as C_0 approaches its maximum value (in region III). Also, in region III, the locking strength of solute atoms decreases significantly because of the high temperatures. The increase of the yield strength depends on the concentration of the atmospheres as well as the locking strength of the solute atoms, and therefore the change in yield strength produced by the dislocation locking should show the same trend as shown in Fig. 5a for the effect of temperature on the concentration of nitrogen at dislocations. Without strain ageing, the yield strength decreases with increasing temperature as shown in curve A in Fig. 5b. Owing to the combination of effects shown in Fig. 5a and b (curve A), the plot of yield strength versus temperature will show a small peak or a plateau in some range of temperature, e.g. as shown in Fig. 5b (curve B). This temperature range, between 423 and 573 K, is the same temperature range where we saw evidence of SSA in our experiment. At even higher temperatures, the locking strength of the atmospheres decreases because of the high diffusivity of the solute atoms, and this results in a decrease in the lower yield strength with increasing temperature, i.e. the same trend as at low temperatures. The interaction

TABLE II Nitrogen concentration (p.p.m.) at different temperatures

	273 K	323 K	373 K	423 K	473 K	523 K	573 K
$\bar{C}/C_0$	2.2×10^5	1.9×10^3	6.2×10	5.3	2.4	1.8	1.5
C_0	0.028	0.3	1.68	6.33	18.0	41.8	83.9
$\bar{C}$	6.1×10^3	5.7×10^2	1.0×10^2	33.5	42.3	75.2	125.9

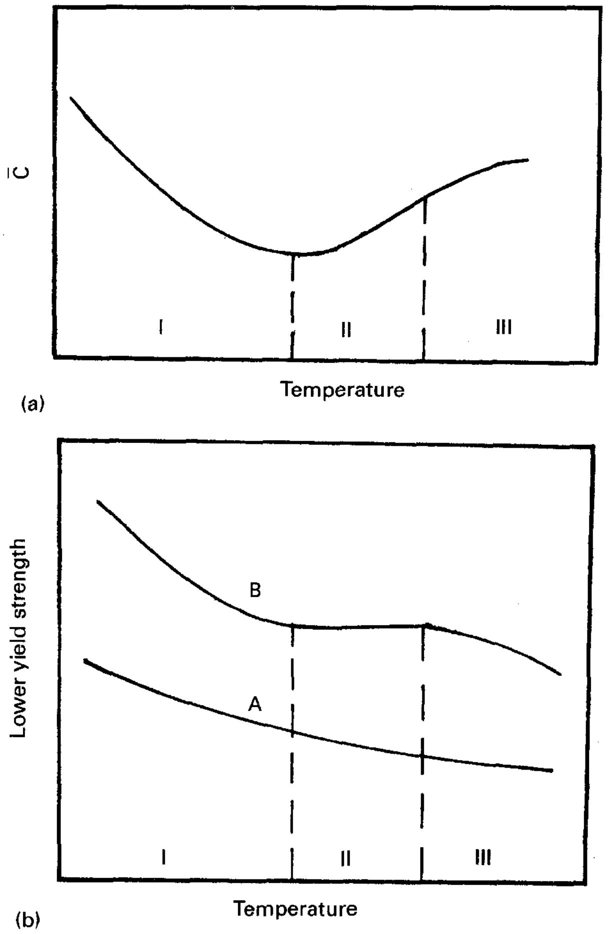

Figure 5 Schematic diagram showing (a) the concentration of nitrogen at dislocations, (b) the effect of temperature on the lower yield strength (A) without SSA, and (B) with SSA.

energy between carbon atoms and dislocations is about the same as that of nitrogen, and therefore the concentration of carbon atoms at dislocations should change with temperature in same way as nitrogen. However, because the solubility of carbon in α-iron is about a hundred times lower than that of nitrogen in this range of temperature, any effects of carbon on SSA should be much smaller than for nitrogen [16], and therefore calculations were not made of carbon concentration at dislocation atmospheres.

5. Conclusions

Mechanical property measurements on three steels over the temperature range 293–623 K and computer modelling of the interaction between nitrogen atoms and dislocations has shown:

1. the lower yield strength of the three low-carbon steels decreases with increasing temperature, but there is a plateau, or a small peak, at temperatures between 423 and 573 K. This is indicative of SSA;
2. the concentration of nitrogen in the atmospheres of dislocations decreases with increasing temperature at temperatures below 423 K and approaches a minimum value at around 423 K. At temperatures above 423 K, the concentration increases with increasing temperature and before finally approaching its maximum value. The concentration of nitrogen at dislocations determines the locking strength of dislocations. The nature of the variation with temperature of the concentration of nitrogen at dislocations results in a plateau, or a small peak, in the yield strength versus temperature curve.

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