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Effect of Strain Aging on the Strength Coefficient and Strain-Hardening Exponent of Construction-Grade Steels

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Two construction-grade steels—G40.21 350 WT and G40.21 350 AT—were tensile tested under a range of temperature and strain-rate conditions. Results showed that both the strain-hardening exponent and strength coefficient at first decrease with increasing temperature, then increase with increasing temperature and reach a maximum at a temperature between 523 and 573 K before decreasing. With increasing temperature, the strain-rate dependence of the strain-hardening exponent and the strength coefficient changes from positive to negative. This behavior reflects the effects of strain aging on the strain-hardening exponent and the strength coefficient.

Keywords

Construction grade steel, mechanical properties, strain hardening, effects of carbon, effects of nitrogen

1. Introduction

IT is well known that strain aging is caused by interactions between solute atoms and dislocations. Solute atoms are attracted by and move to dislocations, where they form solute atmospheres around the dislocations (Ref 1-3). Resistance to dislocation movement is then increased because of locking or dragging of mobile dislocations and strengthening of forest dislocations (Ref 4, 5). This increase in resistance to dislocation movement results in variations in the mechanical properties of materials, and is usually shown as an increase in strength and a decrease in ductility.

Strain aging can be classified into two types: static strain aging and dynamic strain aging, depending on whether the straining and aging processes take place sequentially or simultaneously (Ref 6, 7). The two types of strain aging have different effects on the mechanical properties of materials; usually, static strain aging affects the yield strength, whereas dynamic strain aging affects the plastic deformation and strain-hardening behavior of materials (Ref 8, 9).

The effects of strain aging on the yield strength and flow strength of many materials have been intensively investigated and well documented (Ref 8, 10-15). However, relatively little attention has been paid to the effects of strain aging on strain-hardening parameters, such as the strength coefficient and strain-hardening exponent shown in Eq 1:

$$\sigma = K\varepsilon^n \qquad \text{(Eq 1)}$$

where σ is the true stress, ε is the true strain, K is the strength coefficient, and n is the strain-hardening exponent.

In the opinion of the authors, the strain-hardening exponent, n, expresses the strain-hardening behavior of materials more directly than other parameters, such as flow stress and ultimate strength, and should therefore be affected by dynamic strain aging. The strength coefficient reflects the combined effects of the yield strength and strain hardening and therefore should be affected by both static and dynamic strain aging.

In the present study, two construction-grade steels were chosen as the experimental materials. The effects of temperature and strain rate on the tensile properties, strain-hardening exponent, and strength coefficient of the materials were investigated.

2. Experimental Details

2.1 *Materials*

The materials under investigation were two construction-grade steel plates—G40.21 350 WT and G40.21 350 AT—12.7mm (0.5 in.) and 17.8 mm (0.7 in.) thick, respectively. The plates were produced in a fine-grain condition using fully killed steelmaking practice. The as-received materials were hot rolled. The chemical compositions of the materials are given in Table 1, and typical optical micrographs are shown in Fig. 1. The microstructures consisted of ferrite and pearlite.

2.2 *Specimens*

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

2.3 *Tensile Testing*

Tensile testing was accomplished using a floor model TT Intron machine fitted with a high-temperature furnace to heat the specimens. A chromel-alumel thermocouple attached to the

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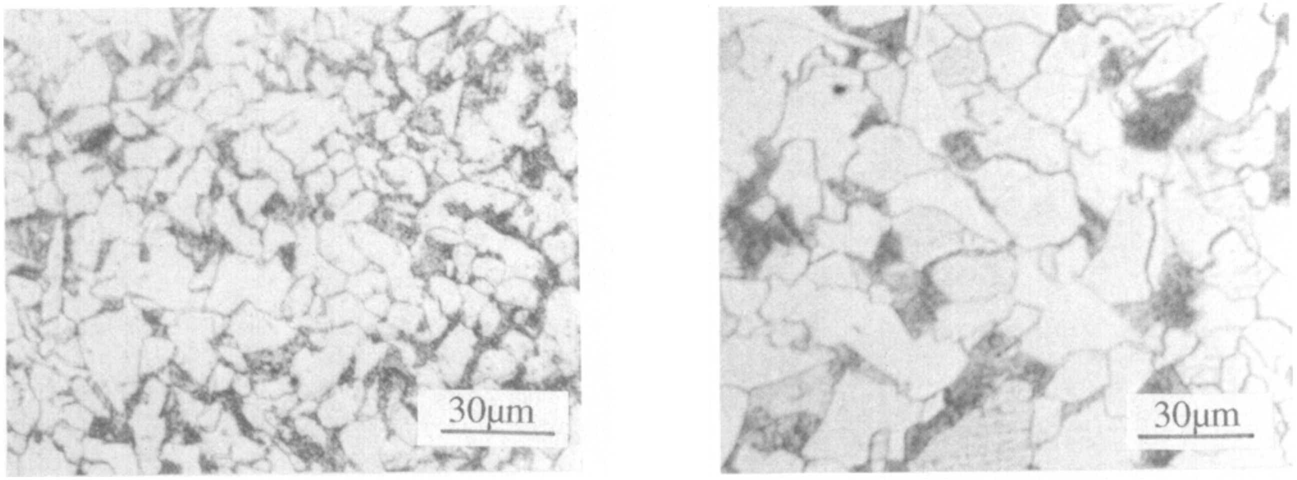
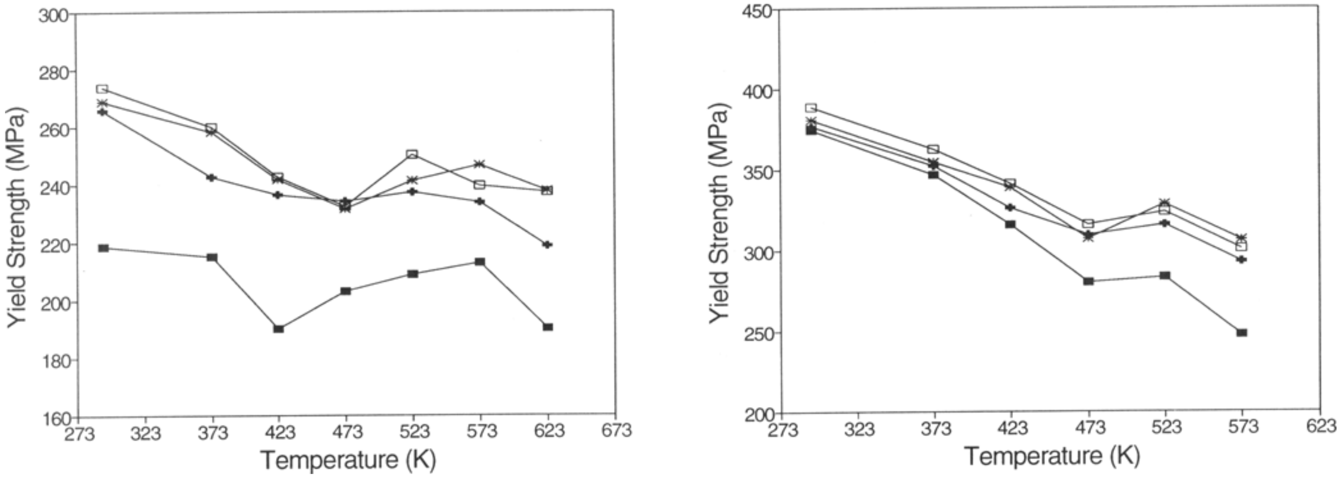


(a) (b)

Fig. 1 Optical micrographs of the plate materials. (a) G40.21 350 WT. (b) G40.21 350 AT



(a) (b)

Fig. 2 Temperature dependence of yield strength. (a) G40.21 350 WT. (b) G40.21 350 AT. Strain rate: ■, 1.48 × 10^{-5}/s; +, 7.41 × 10^{-5}/s; ★, 3.71 × 10^{-4}/s; ☐, 1.48 × 10^{-3}/s

Table 1 Chemical compositions of the plate materials

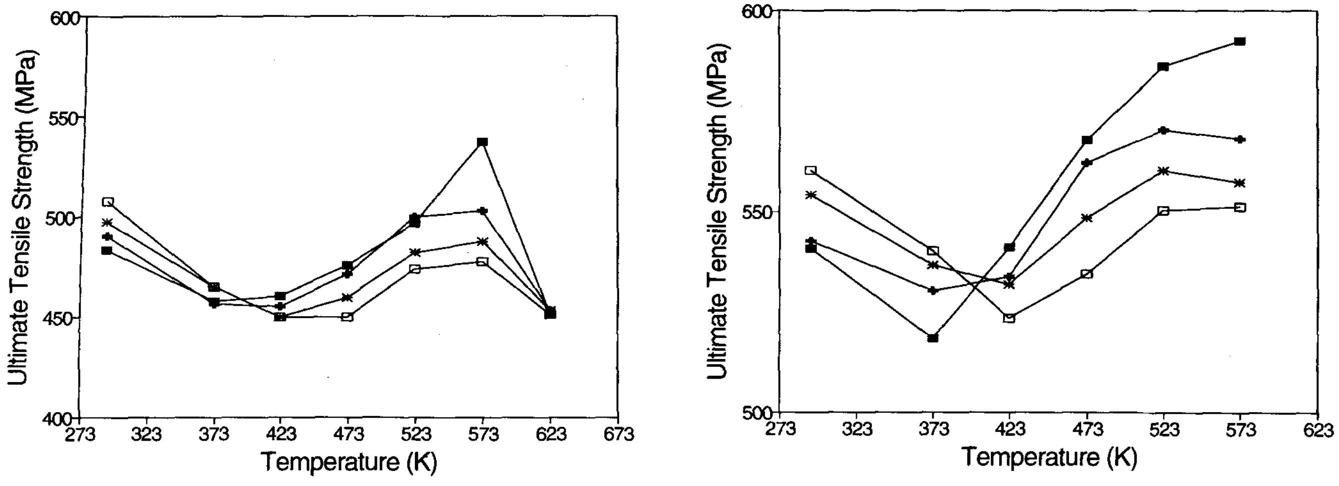
Grade	C	Mn	S	P	Si	Composition, wt% Cr	Ni	Cu	Mo	Al	V	N
G40.21 350 WT	0.19	1.19	0.01	0.006	0.17	0.03	0.02	0.06	0.04	0.039	<0.01	0.0047
G40.21 350 AT	0.13	1.13	0.009	0.007	0.21	0.42	0.37	0.27	0.01	0.039	0.049	0.0063

middle of the specimens was used for temperature measurement and temperature control, which was within ±3 °C. The temperatures used in the experiment were 293 (ambient), 373, 423, 473, 523, 573, and 623 K. The strain rates used were 1.48 × 10^{-5}/s, 7.41 × 10^{-5}/s, 3.71 × 10^{-4}/s, and 1.48 × 10^{-3}/s. Three or four specimens were tested under each temperature/strain-rate condition, and an average value of the property was calculated.

3. Results

3.1 *Effect of Temperature on Yield Strength*

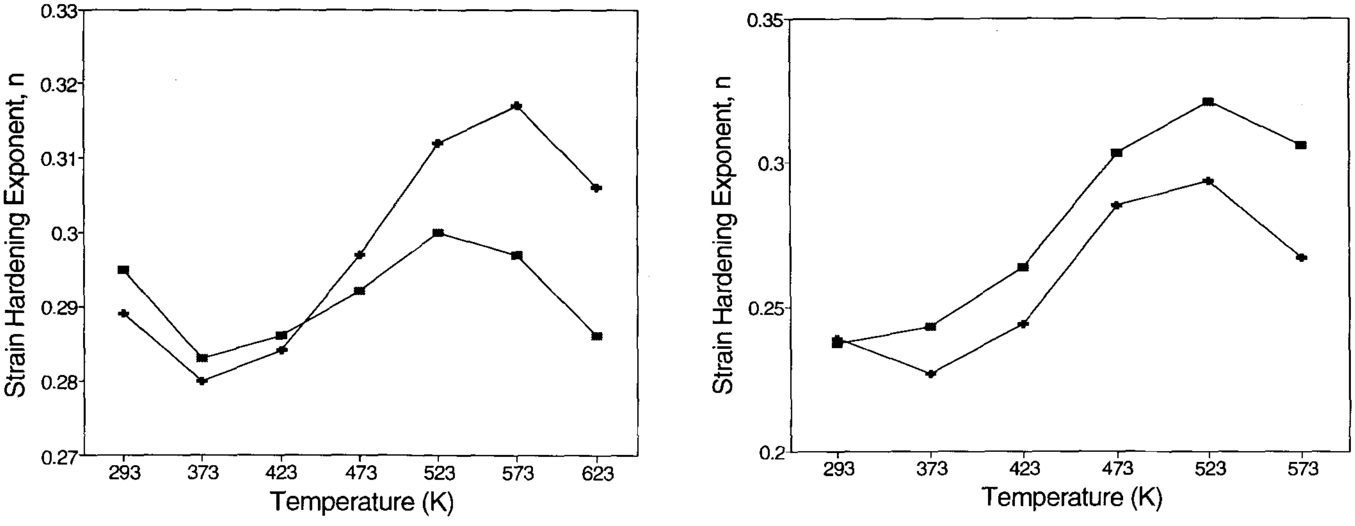
As shown in Fig. 2, the yield strength of the materials generally decreases with increasing temperature. However, a plateau or a small peak in each yield strength/temperature curve occurs



(a)

(b)

Fig. 3 Temperature dependence of ultimate tensile strength. (a) G40.21 350 WT. (b) G40.21 350 AT. Strain rate: ■, 1.48×10^{-5}/s; +, 7.41×10^{-5}/s; ★, 3.71×10^{-4}/s; ☐, 1.48×10^{-3}/s



(a)

(b)

Fig. 4 Temperature dependence of the strain-hardening exponent. (a) G40.21 350 WT. (b) G40.21 350 AT. Strain rate: ■, 7.41×10^{-5}/s; +, 1.48×10^{-3}/s

between 473 and 573 K. Also, the yield strength increases with increasing strain rate.

3.2 *Effect of Temperature on Ultimate Tensile Strength*

As shown in Fig. 3, the ultimate tensile strength (UTS) of the materials varies with temperature. At first, the UTS decreases with increasing temperature and reaches a minimum at a temperature between 373 and 473 K. The UTS then increases with increasing temperature and reaches a maximum around 573 K (Fig. 3a) and 523 K (Fig. 3b) before decreasing with a further increase in temperature. Also, at low temperature, the UTS increases with increasing strain rate; that is, there is a positive dependence of UTS on strain rate. At high temperatures, however, the UTS decreases with increasing strain rate; that is, there is a negative dependence of UTS on strain rate.

3.3 *Effect of Temperature on the Strain-Hardening Exponent*

The calculated strain-hardening exponent (Eq 1) is plotted against test temperature for both materials in Fig. 4. As was the case for the UTS, the strain-hardening exponent decreases with increasing temperature and reaches a minimum at approximately 373 K, then increases with increasing temperature and reaches a maximum at between 523 and 573 K before decreas-

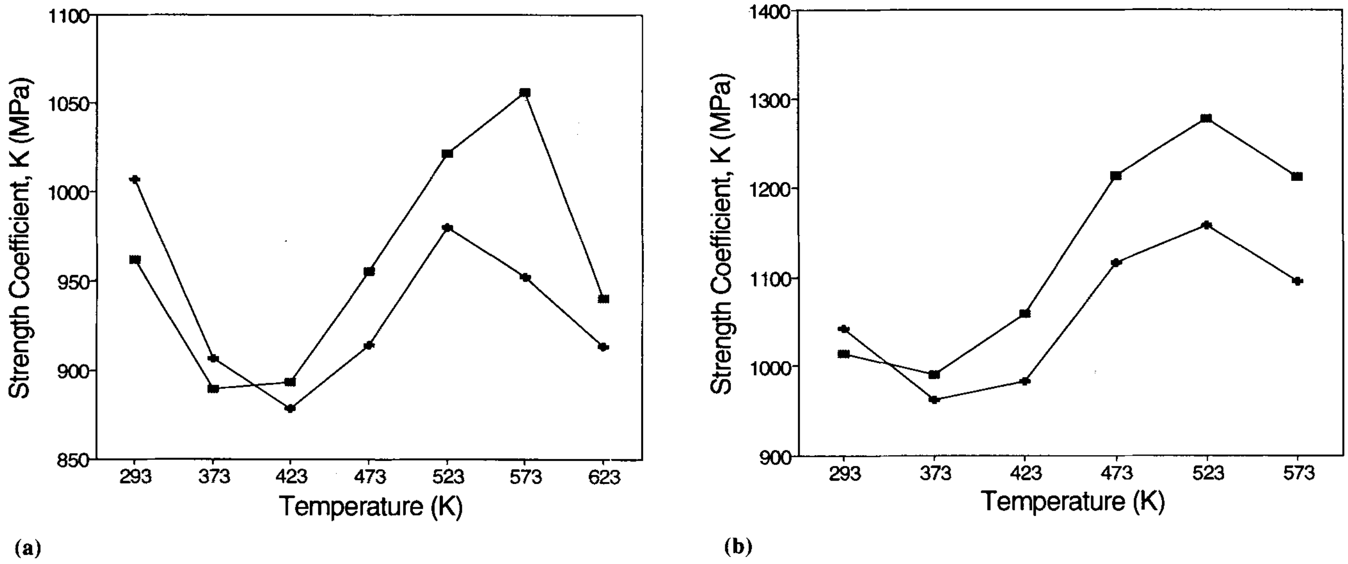


Fig. 5 Temperature dependence of the strength coefficient. (a) G40.21 350 WT. (b) G40.21 350 AT. Strain rate: ■, 7.41×10^{-5}/s; +, 1.48×10^{-3}/s

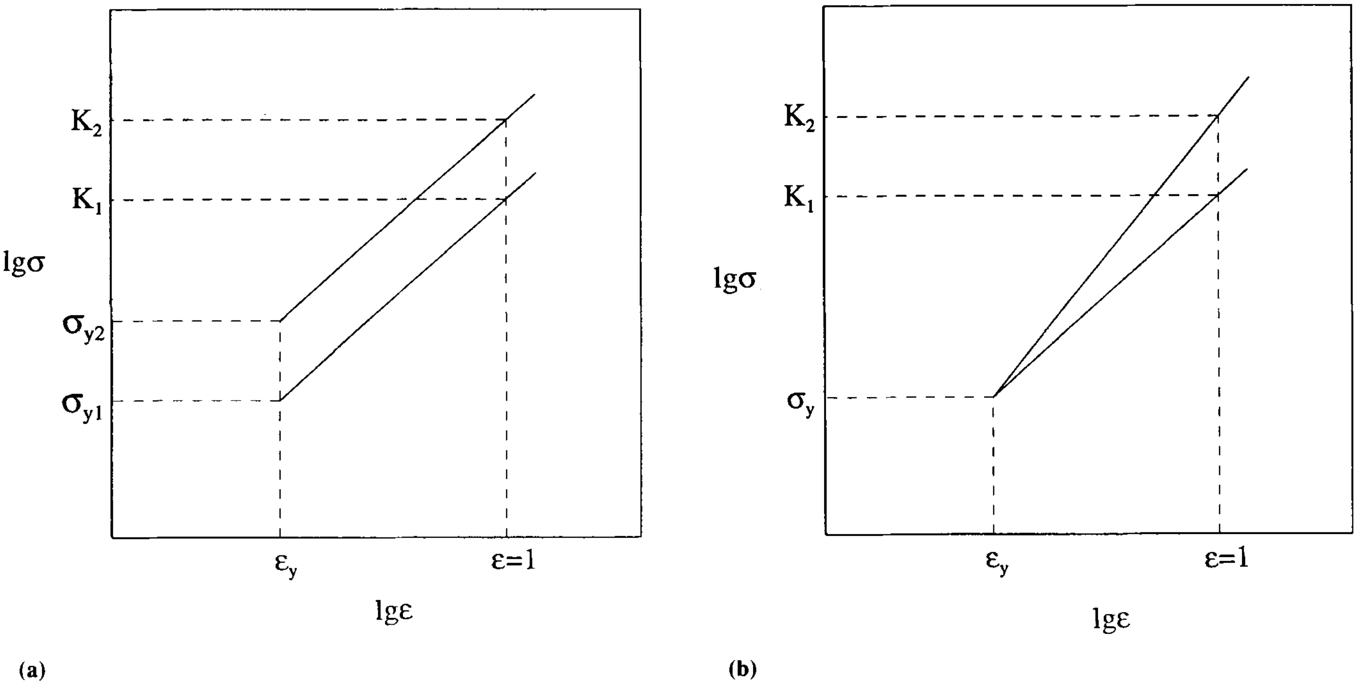


Fig. 6 Schematic diagrams showing the effect of n and σ_y on K. (a) $n_1 = n_2$. (b) $\sigma_{y1} = \sigma_{y2}$

ing with a further increase in temperature. Thus, at low temperatures there is a positive strain-rate dependence of the strain-hardening exponent, but at higher temperatures the strain-rate dependence of the strain-hardening exponent becomes negative.

3.4 *Effect of Temperature on the Strength Coefficient*

The calculated strength coefficient (Eq 1) is plotted against test temperature in Fig. 5. The strength coefficient varies with temperature in the same manner as the strain-hardening exponent.

4. Discussion

As previously noted, static strain aging affects the yield strength of materials, whereas dynamic strain aging affects strain-hardening behavior. The UTS or the flow stress is thus affected not only by dynamic strain aging, but also by static strain aging. As the authors have suggested before (Ref 16), the difference between the UTS and the yield strength, $\Delta\sigma = \sigma_u - \sigma_y$, can be used to evaluate the dynamic strain aging behavior of materials.

The strain-hardening exponent, n, which shows the strain-hardening characteristics of materials directly, can also be used as a criterion to evaluate the effects of dynamic strain aging. However, the strength coefficient, K, is affected by both static and dynamic strain aging, because its "value" combines the effects of the yield strength and the strain-hardening exponent. According to Eq 1, stress-strain curves are straight lines when plotted as log σ versus log ε diagrams, as shown in Fig. 6. In Fig. 6, ε_y is the yield strain, $K = \sigma$ when $\varepsilon = 1$, and n is the slope of a line. In the situation shown in Fig. 6(a), the strain-hardening exponents of two materials are equal ($n_1 = n_2$), but $\sigma_2 > \sigma_1$ and thus $K_2 > K_1$. This means that the higher the yield strength, the higher the strength coefficient. In Fig. 6(b), the yield strengths are equal, but $n_2 > n_1$ and thus $K_2 > K_1$. This means that the higher the strain-hardening exponent, the higher the strength coefficient.

From the results of the present experiments, we can see that with increasing test temperature, the UTS, the strain-hardening exponent, and the strength coefficient decrease at first, then increase to a maximum value before decreasing again. The decrease in these parameters is due to high-temperature softening, whereas the increase reflects the effects of strain-aging hardening over the high-temperature softening (Ref 17). The highest degree of strain aging occurs at a temperature between 523 and 573 K for these two steels. Also, at high temperatures, the strain-rate dependence of n and K changes from positive to negative, in the same manner as the strain-rate dependence of the UTS. This is further evidence of dynamic strain aging.

At room temperature, the strain-hardening exponent of the AT steel is lower than that of the WT steel. This is due to the higher alloying element content of the AT steel. On the other hand, the magnitude of increase in n for the AT steel is higher than that for the WT steel at high temperatures; this implies a higher strain-aging tendency for the AT steel than for the WT steel. The reason for this behavior is, the authors believe, the higher nitrogen content of the AT steel. Many researchers believe that nitrogen, rather than carbon, is a dominant element for strain aging in steels (Ref 18, 19). Even though the AT steel has a lower carbon content than the WT steel, it still has a higher degree of strain aging because of its higher nitrogen content. Because of this higher alloying element content, the yield strength, UTS, and strength coefficient of the AT steel are higher than those of the WT steel at room temperature. At high temperatures, the strength coefficient of the AT steel is higher than that of the WT steel because of its higher yield strength and higher strain-hardening exponent.

5. Conclusions

Studies of two construction-grade steels—G40.21 350 WT and G40.21 350 AT—tensile tested at temperatures from 293 to 623 K and at strain rates from 1.48×10^{-5}/s to 1.48×10^{-3}/s have shown that:

- There is a plateau or a small peak on each yield strength versus temperature curve, and the UTS reaches a maximum at a temperature between 523 and 573 K due to strain aging.
- The strain-hardening exponent, n, is affected by dynamic strain aging in a continuous loading condition, whereas the strength coefficient, K, is affected by both dynamic and static strain aging.
- At a temperature between 523 and 573 K, n and K reach a maximum value for both steels because of strain aging.
- As temperature increases, the strain-rate dependence of the strain-hardening exponent and the strength coefficient changes from positive to negative because of strain aging.

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