Microstructural Size Effect on Strain-Hardening of As-quenched Low Alloyed Martensitic Steels

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Quenched martensitic steels are known to show the characteristic feature of stress–strain relations, with extremely low elastic limits and very large work-hardening. The continuum composite approach is one way to express this characteristic feature of stress–strain curves. Although the overall stress–strain curves, as a function of alloy chemistries of steels, were well represented by this approach, the relationship between the macroscopic deformation behaviors and microstructural information is yet to be clarified. A high-spatial-resolution digital image correlation analysis was conducted to demonstrate the possible unit size corresponding to the microstructure. The continuum composite approach model was also modified to consider the size effect of the microstructure on the stress–strain curves of the as-quenched martensitic steels. Strain concentrations were observed at various boundaries, including lath boundaries, and the characteristic microstructural size was also predicted by the present model, which is smaller than the reported spacing between adjacent strain-concentrated regions.

Keywords: *carbon steel; martensite; stress–strain curve; work-hardening; digital image correlation*

1. Introduction

Martensite is a well-known hardening microstructural component in carbon steels and has been widely applied in the production of high and very high strength steels. Martensite is usually too hard to be plastically deformed. Hence, the microstructure is acceptable for tools, gears, and bearings to resist abrasion and deformities. Martensite is also one of the major microstructural components in the high-strength press formable steel sheets for automotive applications, such as Dual-Phase steels. Even in this case, the plastic deformability of steels is considered to be mainly owed to the deformation of the soft matrix phase, ferrite. When steels with mixed microstructures, including martensite, are strained, non-uniform strain and stress distributions are expected. The strain and stress caused by the microstructural components may depend on their comparative strength, size, crystallographic, and geometrical features. The stress–strain curves of as-quenched martensitic steels are well recognized to show the typical features. They have small elastic limits, very large strain-hardening depending on the carbon concentration of steels, and relatively small ductility. Several mechanisms have been proposed to explain the very low elastic limits of as-quenched martensitic steels. Different approaches have been proposed for the expression of the low elastic limits and very large strain-hardening behaviors of as-quenched martensitic steels. The basic ideas of these studies are very similar, in that they introduce sequential yielding of different localized elements or regions as a generalized Masing method[1)] based on a continuum composite feature of martensite. The first approach is the introduction of a yield strength spectra for local elements[2)], which allows for sequential yielding—depending on the local yield strength of the elements. The second approach is the adoption of pre-existing internal shear residual stresses distributed randomly in different regions[3)] as a result of the sequential formation of martensite laths by the shear transformation mechanism. The residual shear stresses with flat-top distributions were assumed to be set randomly for all the elements within the microstructure. They also adopted the elastic-perfect-plastic stress–strain relation, iso-strain assumption, and Tresca criterion as the yield condition for each element.

Although both models have succeeded in representing experimentally observed stress–strain curves of as-quenched martensitic steels, assuming the heterogeneities of the local mechanical properties, there are some challenges to meet the experimentally observed microstructural heterogeneities due to deformations. The first is the size of the elements discussed in the continuum composite approach (CCA) models. The second point is the strain partitioning among the elements as studied using DIC (digital image correlation) method. And the last point is the assumption of the elastic-perfect plastic deformation behavior assumed in both models.

The aim of this work is to consider the effect of microstructural unit sizes on the strain-hardening of as-quenched martensitic steels, along with an appropriate strain and stress partitioning among different elements in the martensitic microstructures.

2. Extension of Allain's CCA model

A CCA model is adopted in this work, as with previous works by Allain et al.[2)]

Although the origin of the heterogeneity of local yielding has not been experimentally clarified, the CCA model with a yield strength spectrum was adopted here. As discussed by Allain et. al. [2)], function $F\{\sigma\}$ is defined as follows:

$$F\{\sigma\} = \int_{-\infty}^{\sigma} f\{x\}\,dx \qquad (1)$$

where, $F\{\sigma\} = 1$ when $\sigma \to \infty$.

It is also assumed that there is a minimum value, σ_{min}, below which $f\{\sigma\} = 0$ and $F\{\sigma\} = 0$. Although there is no physical reason, the function $F\{\sigma\}$ is assumed to be expressed as follows, as used in Allain's model[2)]:

$$F\{\sigma\} = 1 - exp\left[-\left(\frac{\sigma - \sigma_{min}}{\sigma_0}\right)^n\right] \qquad (2)$$

for the value $\sigma > \sigma_{min}$. The parameter σ_{min} was set to be the experimentally observed elastic limit, as discussed by Allain et al.[2] The parameter σ_0 determines the strength level of the material and is expressed as a function of the UTS or carbon content of the material.

We then adopted the expression of strain-hardening of ferrite reported by Petitgand and Bouazis[4];

$$\sigma\{\varepsilon_p\} = \boldsymbol{\sigma_f} + \alpha M\mu\sqrt{\frac{b}{\beta\Lambda}} \cdot \sqrt{1 - exp(-\beta M\varepsilon_p)} \qquad (3)$$

for strain-hardening of elements after yielding (**Figure 1**),

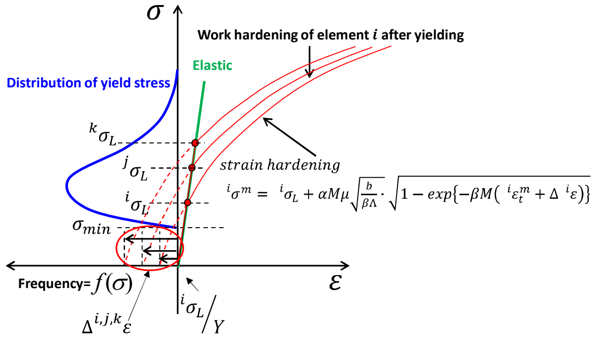

Figure 1 Illustration showing the yield strength spectrum and the strain-hardening model for yielded elements

where M is the Taylor factor; b is the magnitude of the Burgers vector; μ is the shear modulus of ferrite; α is a constant equal to 0.5; Λ is the mean free distance of dislocation movement; β is a parameter for the annihilation rate of dislocations and σ_f is the friction stress of the steel.

The amount of strain-hardening of the $i-th$ element at the $m-th$ step of deformation can be obtained using the derivative the equation (3) with $\varepsilon_p = {}^i\varepsilon_t^m + \Delta\ {}^i\varepsilon$ as illustrated in **Figure 1**. Strain ${}^i\varepsilon_X^m$ expresses the strain of the $i-th$ element at the $m-th$ step of deformation, and $X = t$ for total, p for plastic, and e for elastic strains.

The iso-work assumption[5] is now applied to the model for calculating the magnitude of strain owned by each element at all steps during straining. The total strain increments owned by elements i and j at a straining step m, i.e., $\Delta\ {}^i\varepsilon_t^m$ and $\Delta\ {}^j\varepsilon_t^m$ satisfy the following equation for all i, j pairs:

$$\Delta\ {}^i\varepsilon_t^m \cdot {}^i\sigma^{m-1} = \Delta\ {}^j\varepsilon_t^m \cdot {}^j\sigma^{m-1} \qquad (4)$$

where ${}^i\sigma^{m-1}$ and ${}^j\sigma^{m-1}$ are the stress magnitudes of elements i and j after the previous strain step.

3. Results and discussion

The experimentally observed stress-strain curves reported by Allain et al. were adopted to adjust the model to the experimental data. The parameters, $n, \sigma_0, \Lambda,$ and σ_{min} were determined. It is not surprising that the fitting is extremely good, as shown by Allain et al. for a wide range of stresses and the derivative of stress. The parameter introduced to consider the effect of work-hardening after yielding is the mean free distance, Λ, of the dislocation movement in equation (3). As shown in **Figure 2**, Λ decreased with an increase in the steel carbon content. The mean free distance, Λ, is almost the same order of magnitude as the average lath width reported. The mean free distance may correspond to the average spacing of strain-concentrated regions obtained using DIC (digital image correlation) method. The spacings are reported to be approximately 12 μm by Koga et al.[6], and approximately 20 to 30 μm estimated from the strain distribution obtained by DIC reported by Sugiyama et al.[7] The mean free distance of the dislocation movement obtained in the present work seems to be much smaller than the reported average spacing of the strain-concentrated regions.

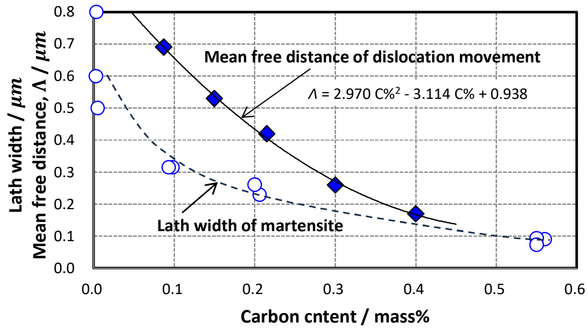

Figure 2 Comparison between mean free distance of dislocation movement and lath width of martensite

Conclusions

CCA model was adopted to understand the microstructural unit size for large work-hardening behaviors in the stress–strain curves of the as-quenched martensitic steels by implementing the iso-work assumption and work-hardening after yielding. The distance of dislocation movement depends on the carbon concentration of the steels and decreases with increasing carbon content. The value obtained for the distance is much smaller than the spacing between adjacent strain-concentrated regions reported previously, but almost the same order of magnitude as the average lath width reported.

Acknowledgments

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References

1) V.G. Masing: Wissenschaftliche Veroffentliebungen aus dem Simens-Konzern, 3(1923), 231 (in German).
2) S. Allain, O. Bouaziz, and M. Takahashi: ISIJ Int., 52(2012), 717.
3) B. Hutchinson, D. Lindell, and M. Barnett: ISIJ Int., 55(2015), 1114.
4) H. Putitgand and O. Bouaziz: Proc. Int. Conf. on the Processing, Microstructure and Properties of IF Steels (IF Steels 2000), ISS, Pittsburg, (2000), 339.
5) O. Bouaziz and P. Buessler: La Revue de Metallurgie, 99(2002), 71.
6) N. Koga, M. Fujita, and C. Watanabe: Mater. Trans., 62(2021), 1424.
7) M. Sugiyama, G. Sawa, K. Hata, and N. Maruyama: Mat. Sci. Eng., 580(2019), 012045.