FEM Modeling of Flow Curves for Ferrite/Pearlite Two-Phase Steels

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Flow curves of ferrite/pearlite two-phase steels were simulated using finite element method (FEM) with regression equations for flow curves of each ferrite and pearlite phase proposed by Hiramatsu et al. and Furukawa et al. The calculated flow strength of ferrite/pearlite two-phase steel was lower than the experimentally measured one mainly due to the underestimation of flow strength of ferrite phase according to the yield elongation. To improve the simulation, the flow curves in homogeneous deformation range were considered. Microscopic observations revealed that most deformation was accumulated in the ferrite phase during yield elongation. Flow curves of ferrite phase were re-evaluated based on this observation and flow curves of ferrite/pearlite steels were also re-calculated. Recalculated yield strength of ferrite/pearlite steels showed good agreement with measured ones, however the work hardening rate of re-calculated flow curves is still lower than that of measured one. The simplicity of pearlite morphology for FEM analysis is thought to be responsible for lower work hardening behavior of calculated flow curve by FEM than that of measured one.

KEY WORDS: ferrite/pearlite steel; finite element method; simulation; flow curve; homogeneous deformation; yield elongation.

1. Introduction

Since many physical and mechanical properties of materials are closely related to their microstructure, technologies to control the microstructure of materials have been well developed to obtain suitable properties. In ferrous alloys, the relationships between the microstructure and mechanical properties are well understood and utilized in many processing technologies. Understanding of the evolution of microstructure during the manufacturing processes becomes more important than ever before. Extensive studies for online prediction of microstructure and mechanical properties of steels have been carried out since 1980’s. The key elements in these technologies are to establish a mathematical model to simulate the microstructural evolution during manufacturing processes and to evaluate mechanical properties of the product according to the resultant microstructure.

There are several reports on the evaluation of the mechanical properties of materials from their microstructure. These include regression methods according to the chemical composition of steels, secant method using Eshelby’s model, and finite element method (FEM). Among these approaches, FEM has the advantage to model the microstructural morphologies closer to the actual ones. Shikanai et al. and Bae et al. applied FEM with a unit cell model to evaluate the influence of microstructural morphology on the mechanical behavior of dual phase steels. Hüper et al. also used FEM analysis with micromechanics to evaluate the stress-strain relationship of ferrite/martensite and ferrite/bainite dual phase steels. FEM analysis has been mainly applied to the evaluation of mechanical behaviors of ferrite-martensite dual phase steel though ferrite/pearlite is most common microstructure of steel plate.

In this study, we attempted to simulate the flow curves of ferrite/pearlite two-phase steels by FEM using a microstructural unit cell derived from the quantitative microstructural analysis. Empirical equations reported by Hiramatsu et al. and Furukawa et al. were adopted to estimate the flow strength of ferrite and pearlite phase. Ferrite/pearlite two-phase steel shows remarkable yield elongation during deformation, which is negligible for ferrite/martensite dual phase steel. The effect of yield elongation on the FEM simulation of flow strength is discussed and a method to improve the simulation is suggested. The effect of stress concentration according to complexity of pearlite morphology on the work hardening behavior of flow curve calculated with FEM is also discussed.

2. Experimental

The chemical compositions of two low carbon steels used in this study are given in Table 1. The steel plates were hot rolled at above A₃ temperature and then air cooled. The initial and final thickness of plates was 250 mm.
and 15 mm, respectively. Optical and scanning electron micrographs were used to measure the grain size of ferrite phase and interlamellar spacing of pearlite. The method suggested by Ridley was used to measure the interlamellar spacing of pearlite. The area fraction and size of pearlite islands were measured with an image analyzer. Average thickness of pearlite islands was measured by line intersection method along thickness of steel plates on longitudinal cross-section. The aspect ratio of pearlite was determined from the average area and the average thickness of pearlite islands. Longitudinal tensile test specimens were machined from the plates in accordance with ASTM E-8 standard (gauge length: 30 mm, \( \phi \): 6 mm) and the experimental flow curves of each steel plate were evaluated by universal tensile test machine at the cross head speed of 10 mm/min.

Typical microstructures of plate A and B are given in Fig. 1 and the measured microstructural parameters are given in Table 2. In both steel plates, pearlite shows banded structure due to the segregation of substitutional alloy elements. The aspect ratio of the banded pearlite in plate B is higher than that in plate A. The flow curves of plate A and B are given in Fig. 2.

### Table 1. Chemical compositions of steels used in this study. (in mass%)

|       | C   | Si  | Mn  | P   | S   |
|-------|-----|-----|-----|-----|-----|
| Steel A | 0.15 | 0.21 | 0.5  | 0.012 | 0.008 |
| Steel B | 0.15 | 0.25 | 1.3  | 0.012 | 0.005 |

### Table 2. Measured microstructural parameters of Specimens.

|       | Grain size of ferrite(\(\mu m\)) | Interlamellar spacing of pearlite(\(\mu m\)) | Volume fraction of pearlite | Aspect ratio of pearlite island |
|-------|----------------------------------|----------------------------------|---------------------------|--------------------------------|
| Steel A | 23.6                             | 0.12                             | 0.18                      | 3.8                            |
| Steel B | 20.4                             | 0.10                             | 0.24                      | 6.9                            |

### Fig. 1. Optical micrographs of steels A and B.
(a) Steel A (b) Steel B

### Fig. 2. Experimental flow curves of steel A and steel B.

### Fig. 3. Simplified model of microstructures for ferrite/pearlite two-phase steel.

### Fig. 4. Initial meshes and boundary conditions for finite element method. (Steel B)

### 3. Simulation
#### 3.1. Unit Cell and Boundary Condition
The 2-dimensional finite element method with a unit cell model suggested by Bae et al. was used to simulate the flow behavior of ferrite/pearlite steels. The microstructure of ferrite/pearlite steels was patterned as shown in Fig. 3 with measured aspect ratio and volume fraction of pearlite listed in Table 2. Initial meshes and boundary conditions for the FEM calculation are given in Fig. 4. The area OABC is the...
unit cell which represents the mechanical property of the whole material. The displacement of symmetric plane (OC and OD) to vertical direction of each symmetric axis (Y and X) was fixed during deformation, and displacement to X- and Y-direction of origin (O) was also fixed. The plane DE could not remain linear during deformation because no restriction on the plane DE allows free contract along X-direction. This uneven lateral contraction can affect the mechanical behavior of the unit cell, which is called the edge effect. This edge effect became small with an increase in the number of unit cell along X-direction.5) Nine unit cells along X-direction as shown in Fig. 4 is sufficient for making the edge effect on the unit cell OABC negligible.5) The Young’s modulus of 201GPa and Poisson’s ratio of 0.3 were used for calculation.

3.2. Evaluation of Flow Curves of Ferrite and Pearlite Phases

The empirical equations suggested by Hiramatsu et al.7) and Furukawa et al.8) were used to evaluate the flow strength of ferrite and pearlite phases. To describe the flow curves of ferrite and pearlite phases, they used following Swift’s equation.

\[ \sigma = a(b + \varepsilon_p)^N \]

where \( \sigma \) and \( \varepsilon_p \) are true stress and true strain, respectively. The material constants \( a, b \) and \( N \) of the Swift’s equation were presented as a function of chemical composition and microstructural parameters such as grain size of ferrite and interlamellar spacing of pearlite. The coefficients of the equation were evaluated using regression method7–8) and are shown in Table 3.

To evaluate the flow curves of ferrite and pearlite, microstructural parameters of ferrite and pearlite; chemical composition of ferrite and volume fraction of cementite in pearlite are needed. The results of Table 2 were used for microstructural parameters of ferrite and pearlite. For estimation of chemical composition of ferrite, partitioning of substitutional elements was neglected and the carbon content of ferrite was determined from the maximum solubility limit of carbon in ferrite calculated from (Fe, Mn)–C pseudo-binary phase diagram. 0.012 mass% and 0.007 mass% were used as carbon contents of ferrite in steel A and B, respectively. Volume fraction of cementite in pearlite was assumed to be 0.12 for both steels, which was the equilibrium volume fraction of cementite in pearlite of Fe–C system.

4. Results and Discussion

4.1. Flow Curves of Ferrite/Pearlite Two Phase Steel

Figure 5 shows the calculated flow curves of the ferrite and pearlite phases from the material parameters listed in Table 3. The strengths of pearlite and ferrite in steel B are higher than those of steel A, because of higher Mn content, smaller ferrite grain size and smaller pearlite interlamellar spacing in steel B. All flow curves in Fig. 5 show continuous yielding as the adopted Swift type equation suggests. Thus only continuous flow curves of ferrite plus pearlite composites are expected by this type of simulation.

Figures 6(a) and 6(b) show the measured and calculated flow curves of steel A and B, respectively. The measured flow curves show the typical yield elongation in both steels, but the calculated flow curves exhibit no yield elongation. The calculated yield and flow strengths of steel A and B with FEM are lower than the experimentally measured values and the difference between the calculated and experimental flow strengths increases with the increase in strain.

The lower estimation of yield strength by simulation is believed to intrinsically originate from under-estimation of yield strength of ferrite by Swift equation. Figure 7 is a schematic diagram which shows the under-estimation of yield strength of the ferrite phase by Swift type equation.7) When the equation is extrapolated to yield elongation, the yield strength of ferrite is inevitably underestimated.

4.2. Evaluation of Flow Curve in Homogeneous Deformation Range

If Lüders strain during yield elongation of ferrite, \( \varepsilon_p \) is properly evaluated, using a flow curve of ferrite which is composed of yield elongation and Swift type curve for homogeneous deformation can be one of the calculation

| Table 3. The empirical equations to evaluate the mechanical properties of ferrite and pearlite phases.7,8) |
|----------------|-----------------|-----------------|
|                | Ferrite          | Pearlite         |
| Swift equation | \( \sigma = a(b + \varepsilon_p)^N \) | \( \sigma = a(b + \varepsilon_p)^N \) |
| \( a \)        | \( 1.55 \times 10^6[\text{C}] + 3.18 \times 10^6[\text{Ca}] + 142[\text{Si}] + 51.3[\text{Mn}] + 2.11 \times 10^7[\text{P}] + 1.32 \times 10^7[\text{Nb}] + 428d^{1/2} + 457 \) | \( 4.25 [\text{C}] - 52.0[\text{Ca}] + 2.04 \times 10^{-7}[\text{Si}] + 7.89 \times 10^{-7}[\text{Mn}] + 1.16[\text{P}] - 3.38[\text{Nb}] - 0.459d^{1/2} + 0.307 \) |
| \( b \)        | 0.002            | 0.002            |
| \( N \)        | 2.005            | 2.100            |
| \( \varepsilon_p \) | 0.12            | 0.12             |

[\text{element}] : mass% of each element
[\text{C}] : mass% of the solute carbon in ferrite.
d : grain size of ferrite in \( \mu \text{m} \)
\( S_p \) : interlamella spacing of pearlite in \( \mu \text{m} \)
\( F_p \) : the volume fraction of cementite in pearlite.
method to consider yield elongation of ferrite/pearlite two-phase steel. However, there is discontinuous propagation of Lüders band during yield elongation and such discontinuous behavior of materials cannot be considered in simulation even though flow curve of ferrite, which is composed of yield elongation and Swift type curve for homogeneous deformation, is used for FEM analysis.

Since FEM cannot properly simulate discontinuous yield behavior of ferrite, simulation of the flow curves of ferrite/pearlite steel only in homogeneous deformation range was attempted in this study. Both pearlite and ferrite phases can deform during yield elongation. Therefore, it is necessary to evaluate the contribution of each phase to yield elongation.

Figures 8(c), 8(d) and 8(e) show transmission electron micrographs for steel B after yield elongation. As shown in Figs. 8(d) and 8(e), dislocations are developed in ferrite near the ferrite/pearlite interfaces as well as in ferrite grains. Compared to Fig. 8(b) which shows ferrite/pearlite interface before deformation, Figs. 8(d) and 8(e) show that significant strain accumulates in ferrite during yield elongation. The microstructural changes of pearlite before and after yield elongation are given in Figs. 8(a) and 8(c). Dislocations are developed locally during yield elongation as shown in Fig. 8(c), but when compared with the microstructural changes of ferrite, the changes in pearlite are not significant.

Assuming that only ferrite deforms during yield elonga-
tion, the average strain of ferrite phase, $\varepsilon_f$, after yield elongation can be expressed as follows.

$$
\varepsilon_f = \ln \left[ 1 + \frac{1}{v_f} \exp(\varepsilon_y) - 1 \right]
$$

where $\varepsilon_y$ is the Lüders strain of the steels and $v_f$ is the volume fraction of ferrite. $\varepsilon_y$ could be experimentally measured by tensile test and determined to be 0.03 for the present steels. If average strain of ferrite phase after yield elongation is evaluated to be $\varepsilon_f$, the flow curve of ferrite phase after yield elongation can be obtained by shifting the flow curve of ferrite phase by $\varepsilon_f$. Therefore, the mechanical properties of ferrite phase after yield elongation will be evaluated as schematically shown in Fig. 9.

Flow curves of ferrite/pearlite steels in homogeneous deformation range were calculated by FEM from re-evaluated flow curve of ferrite phase. Re-calculated flow curves of ferrite/pearlite two-phase steels from modified flow curves of ferrite are shown in Fig. 10. The flow curves expected by the rule of mixture are also given in Fig. 10. The yield strength of ferrite/pearlite two-phase steel is successfully predicted with modified method. The calculated yield strength of ferrite/pearlite steel compared with measured one is given in Fig. 11. According to the re-evaluation of yield strength of ferrite, the calculation results on yield strength of ferrite/pearlite two-phase steel are remarkably improved.

The calculated results by FEM agree well with the experimental results in the early stage of deformation but deviate at later stages. The difference between the calculated flow strength and experimentally measured one increases as deformation proceeds. The calculation result from rule of mixture shows relatively better agreement with experimental data at high strain region.

Lloyd et al.\textsuperscript{12} studied the effects of particle morphology on the mechanical behavior of Al/(SiC)\textsubscript{p} composite by FEM and reported that the composite materials with the cuboidal particles had a higher strain hardening rate than those with spherical particles. Higher stress concentration in and around the cuboidal particles is reported to be responsible for this behavior. The same argument can be applied to the present results and the trend will be more eminent as the morphologies of the particles become more complicated. The banded pearlite in hot rolled steel plates doesn’t have such a simple morphology as assumed in this model. As can be seen in Fig. 1, the ferrite/pearlite interfaces are far more complicated than the interfaces of unit cell shown in Fig. 4. Higher stress concentration and more strain distribution in harder pearlite phase are expected during deformation and these may lead to higher work hardening rate than present result calculated from very simple morphological model. However, FEM modeling with unit cell which exactly represents real microstructure is not feasible yet, although various structural models have been used for FEM analysis of two-phase steel.\textsuperscript{4,6,13} In this study, in an attempt to demonstrate the effect of complexity of
pearlite morphology on stress concentration and work hardening behavior of ferrite/pearlite steel, a flow curve of steel A is calculated with morphology of pearlite in Fig. 12, which shows more complicated morphology compared with that of calculated with unit cell model of Fig. 4. The calculated flow curves and distributions of effective stress in unit cell according to the morphology of pearlite are shown in Figs. 13 and 14. The distributions of calculated effective stress at 0.14 in effective strain level shows that the stress concentration on complicated morphology of pearlite is higher than that of simple morphology of pearlite. The stress concentration in the case of the unit cell with more complicated pearlite morphology leads to higher work hardening behavior than that of with simple pearlite morphology as shown in Fig. 13. This result demonstrates that the morphological characteristics of pearlite should be further considered for the better simulation of flow curves of ferrite/pearlite two-phase steels.

5. Conclusion

The flow curves of ferrite/pearlite steels were calculated using FEM from the empirical equations of the flow curves of each ferrite and pearlite phase. The calculated flow strengths of ferrite/pearlite steels were lower than the experimentally measured ones. Underestimation of yield strength of ferrite with Swift type equation is discussed as a major source of discrepancy. Microstructures before and after yield elongation of ferrite/pearlite steels revealed that most of the deformations occurred in ferrite phase during yield elongation. Modified flow curves in homogeneous deformation range considering the ferrite deformation during inhomogeneous yielding showed better agreement with experiments. Morphological characteristics of pearlite should be further considered for the better simulation of flow curves of ferrite/pearlite two-phase steels.

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