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On the yield point phenomenon in low-carbon steels with ferrite-cementite microstructure

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ABSTRACT

Low-carbon steels with a ferrite-cementite microstructure represent a discontinuous yielding resulting in several industrially undesirable problems. Considering the thermal contraction mismatch between the ferrite and cementite phases during the cooling stage to room temperature, which is comparable with the volume expansion due to austenite to martensite transformation, one may expect that these steels, similar to dual-phase steels, exhibit a continuous yielding behavior. In order to examine this phenomenon, different microstructures including ferrite-cementite, ferrite-cementite-martensite and ferrite-martensite were produced using a low-carbon steel and yielding behavior of steel samples with these microstructures were evaluated during uniaxial tensile loading. In addition, the effect of volume expansion due to austenite to martensite transformation and thermal contraction mismatch between ferrite and cementite phases on each microstructure was also evaluated. It was found that for the case of ferrite-cementite steels with very small cementite particles, continuous yielding cannot be observed. Finally, yielding behavior of different steel samples were explained based on the theoretical results obtained.

1. Introduction

Due to the existence of solute interstitials such as carbon and nitrogen atoms, low carbon steels like many metals and alloys exhibit discontinuous yielding manifesting itself in the appearance of a sharp yield point and subsequent yield plateau in the stress-strain curve. By diffusing to the dislocation sites, solute atoms hinder the movement of dislocations. In order to unlock these dislocations, a certain stress is required which is known as the upper yield stress. When the stress level reaches the upper yield stress, dislocations will be released at the stress concentration sites. After releasing, dislocations could move with a lower stress level corresponding to the lower yield stress. The stress drop at the yield point is accompanied by the nucleation of slip bands named Lüders bands at the points of stress concentration. Since stress concentration is generated at the Lüders bands front, dislocations are gradually unlocked in elastically deformed sections of the specimen and propagation of the Lüders bands along the whole gauge length of the specimen is enabled. Since Lüders bands propagate under a constant stress level equals to the lower yield stress, a plateau is formed in the stress-strain curve called the yield point elongation [1,2].

Causing industrially important problems, the yield point phenomenon in carbon steels has been investigated for several decades. Besides early studies on explaining the mechanism of discontinuous yielding in such steels, the influences of many factors such as ferrite grain size, type of the steel microstructure, strain rate, deformation temperature and carbon content on discontinuous yielding, the magnitude of Lüders strain and the velocity of Lüders bands front have been studied [3–10].

Formation of a certain amount of martensite phase in the microstructure of low carbon steels leads to a continuous yielding behavior. Elimination of the yield point phenomenon has been attributed to introducing mobile dislocations into the ferrite matrix as a result of volume expansion accompanying austenite to martensite transformation. Internal stresses produced due to austenite to martensite transformation have been also considered to be responsible for continuous yielding behavior [11–13]. On the other hand, in the stress-strain curve of low carbon steels with ferrite-cementite microstructure during uniaxial tensile loading, yield point phenomenon is also observed. Considering the thermal contraction mismatch between the ferrite and cementite phases generated upon cooling, which is comparable to the volume expansion due to austenite to martensite transformation, a very important question arises that why continuous yielding behavior could not be observed in the stress-strain curve of these steels with ferrite-cementite microstructure. The present research work is an effort to account for this question. In order to achieve this

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Nomenclature

M_s	Martensite start temperature
$\Delta V_{\gamma \to \alpha}$	Difference between the specific volumes of austenite and martensite phases
V_γ	Specific volume of austenite
C	Carbon content of martensite in weight percent
ε_M^*	Transformation strain of martensite
ε_c	Transformation strain of cementite
ε_c^*	Equivalent transformation strain of cementite
α_I	Thermal expansion coefficients of cementite phase
α_M	Thermal expansion coefficients of ferrite phase
ΔT	Temperature change
C_I	Stiffness tensor of inclusion (cementite particle)
C_M	Stiffness tensor of matrix (ferrite phase)
S	Eshelby tensor
δ_{kl}	Kronecker delta
a	Radius of second phase particle (martensite or cementite)
R	Radius of plastic zone formed around the particle due to internal stress induced yielding of matrix
$\varepsilon(r)$	Equivalent plastic strain
E	Young's modulus
ν	Poisson's ratio
Y_o	Yield strength of ferrite at the temperature of internal stress induced yielding
α	Constant
E	Energy of interaction of solute atoms and dislocations in Eq. (10).
c	Concentration of solute atoms
k	Boltzmann's constant
T	Temperature
b	Burgers vector
K_{HP}	Hall-Petch parameter
D	Grain size of ferrite phase
M	Taylor factor
G	Shear modulus
d	The diameter of the particle
L	Mean particle spacing
f	Volume fraction of particles
Y	Yield strength of ferrite
ρ_{GND}	Average density of geometrically necessary dislocations (GNDs)
γ	Shear strain
ε	Normal strain
$f_{\min}$	Minimum volume fraction of the second phase required for the occurrence of internal stress induced yielding of ferrite throughout the microstructure
$\bar{\sigma}$	Equivalent stress
σ_m	Mean normal stress
H_o	Initial strain hardening rate of the ferrite at internal stress induced yielding
σ_A	Uniaxial tensile stress
$\bar{\sigma}_A$	Weighted average yield stress in the internal stress induced yielded zone
θ	The angle from the $x_1 - x_2$ plane to the r direction with the assumption that the tensile stress acts in the x_3 direction
σ_s	Stresses required for operating dislocation sources
σ_i	Stresses required for overcoming obstacles to the motion of dislocations produced by the sources
γ	Amount of crystallographic slip in Eqs. (27) and (29) generated by the dislocations moving a certain distance
ρ	Dislocation density
l	The distance moved by dislocations
f_{PZ}	Volume fraction of plastic zones generated by internal stress

goal, the yielding behavior of steels with different microstructures including ferrite-cementite, ferrite-cementite-martensite, and ferrite-martensite microstructures has been investigated theoretically.

2. Experimental procedure

A low carbon steel in the form of a sheet 4.6 mm in thick was used in this research work. The chemical composition of the investigated steel is given in Table 1. Samples with the size of 80 mm × 15 mm were cut from the sheet and then, were austenitized at 1000 °C for 30 min followed by quenching in an ice brine solution. The resulting martensitic steel was tempered at 650 °C for 1 h and then, was cold rolled by a 80% reduction using a laboratory rolling mill with the roll diameter of 57 cm. The cold rolled samples were tempered for another 2 h at 650 °C. This treatment resulted in a microstructure consisting of cementite particles in a ferrite matrix. The samples with ferrite-cementite microstructure are labeled “F” throughout the paper. In order to produce different volume fractions of martensite in steel microstructures, some of the samples with ferrite-cementite initial microstructure were intercritically annealed at 740 °C for 30 s, 1 and 15 min followed by quenching into an ice brine solution. Consequently, two types of microstructures including ferrite-cementite-martensite (labeled “B”) and ferrite-martensite (labeled “C”) were produced. The microstructures of steel samples were investigated using scanning electron microscope (SEM) (Leo 1450VP). Samples for microstructural examination were etched with 3% Nital solution. The sizes of martensite islands and cementite particles as well as the volume fractions of martensite and cementite phases were measured using Clemex image analysis software. In order to evaluate yielding behavior, tensile tests were conducted on specimens prepared according to ASTM-E8 standard with a 25 mm gauge length and the strain rate of 0.002 s^{-1} using Zwick Z250 universal tensile test machine. In order to obtain stress-strain curve of ferrite, specimens of a steel containing 0.09 wt% carbon were also tested.

3. Results of the tensile testing

The results of quantitative metallography for each specimen are presented in Table 2. The microstructures of these specimens are

Table 1
Chemical composition of the steel used in this study in weight percent.

Fe	C	Mn	Si	P	S	Cr	Ni	Mo	Al	Cu	Co	Ti	Nb	V	W
Balanced	0.165	1.15	0.411	0.018	0.01	0.035	0.066	0.008	0.042	0.062	0.001	0.001	0.001	0.001	0.028