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Interphase precipitation in vanadium-alloyed steels: Strengthening contribution and morphological variability with austenite to ferrite transformation

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Abstract

The evolution of characteristic features of interphase precipitation in steels with progressive of austenite-to-ferrite transformation is analyzed from both experimental and modeling approaches. The model developed describing the time and temperature evolution of sheet spacing and particle spacing shows good agreement with the experimental data. The interactions between the transformation and interphase-precipitated carbides are discussed, and particular attention is paid to the occurrence of fibrous carbides. It is suggested that the ease of interface motion is the main factor controlling its appearance. Finally, the local strengthening in a single ferrite grain containing different precipitation states is analyzed by nanoindentation and compared with the theoretical calculations. The evolution of strengthening induced by interphase precipitation with the microstructural parameters is then discussed.

Keywords: Ferrite transformation; Interphase precipitation; Steels; Carbide; Modeling

1. Introduction

The development of modern steels depends on the increased understanding of both precipitation and phase transformation. That is why it was an active field of research all through the 20th century [1–3]. In the case of steels micro-alloyed with Ti, Nb and V, it has been found that the decomposition of austenite (γ) is often accompanied by carbide precipitation. In addition to the carbides commonly precipitating from supersaturated ferrite (α), two distinctive carbide aggregates, interphase precipitation (IP) and carbide fiber (CF), are found to originate from the α/γ interface under particular conditions [4–6]. The case of IP has received considerable attention [4,7–10] because such a carbide aggregate is beneficial for developing advanced high-strength steels while keeping considerable formability [8,11]. Owing to these remarkable features, numerous experimental studies have been carried out to propose possible mechanisms [12,13] and to develop models [14–18] based on microstructural analysis. Beyond the qualitative observation of IP, it is observed that the sheet spacing, precipitate size and morphologies of precipitates change during progressive $\gamma \rightarrow \alpha$ transformation [19]. This variability is one of the main focuses of this paper.

Systematic research concerning IP was initiated by Honeycombe et al. [4,9,10,20], and the ledge mechanism of $\gamma \rightarrow \alpha$ transformation was proposed to explain the banded structure of carbides in the α matrix. It has been reported that IP carbide is associated with a semi-coherent $\{1\ 1\ 0\}_\alpha || \{1\ 1\ 1\}_\gamma$ interface and exhibits a single variant of Baker–Nutting orientation relationships [21],

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List of symbols

a	ferrite lattice parameter
R	carbide radius
h	ferrite ledge height
f_p	carbide volume fraction
f_a	ferrite volume fraction
f_γ	austenite volume fraction
α	ferrite
γ	austenite
κ	correction factor for Orowan equation
λ	sheet spacing
b	Burger's vectors
b_p	particle spacing
J_B	ferrite nucleation rate
J_p	carbide nucleation rate
M	mobility of unit ledge
M_T	Taylor's factor
N	number of carbides per unit volume
G	shear modulus of ferrite
ΔG	driving force for $\gamma \rightarrow \alpha$ transformation
ΔG_α^m	free energy change associated with the formation of ferrite nucleus per unit volume
ΔG_p^*	maximum of Gibbs energy associated with the formation of a carbide nuclei
ΔG_α^*	2-D maximum of Gibbs energy associated with the formation of a ferrite nuclei
Q^α	activation energy for attaching an iron atom to the critical ledge nucleus
$v_{\alpha\gamma}$	overall interface velocity
D	boundary diffusivity of solute atom
$\sigma_\circ$	α/γ interfacial energy
c_p°	nominal solute concentration
c_p^α	solute concentration in ferrite
c_s^p	solute concentration in carbide
c_p^γ	solute concentration in austenite
c_c^γ, c_γ	carbon concentration in austenite
c_c^α	carbon concentration in ferrite
c_c^p	carbon concentration in carbide
c_{crit}	critical solute content for carbide precipitation
V	the ratio of molar volume of precipitate to ferrite

$(0\ 0\ 1)_{MC}||(0\ 0\ 1)_\alpha$ and $[1\ 1\ 0]_{MC}||[1\ 0\ 0]_\alpha$ with respect to the α matrix. Smith and Dunne [22] further categorized IP by its distribution, and the single variant selection of IP carbides was explained by the interfacial energy of carbide/α and the diffusion efficiency of solute atoms. Their studies constructed the basic understanding of IP, and some of their propositions and observations have been used in past decades to develop models to predict the features of IP.

In vanadium-alloyed steels, Todd et al. [23] were pioneers in proposing a numerical model to predict the features of IP. They examined in detail the diffusion profile in front of the α/γ interface and introduced a "pseudo-phase" at the interface in their calculations. The characteristic features of IP could be estimated theoretically, but the ledge mechanism of $\gamma \rightarrow \alpha$ transformation was not emphasized in their model. Rios [18] used the mass balance of vanadium solute in a defined diffusion zone (pseudo-phase). His calculations were based on volume diffusion of vanadium and limited to the case of the stoichiometric ratio of V/C. Rios considered the ledge mechanism, but assumed that the α ledge height was fixed and always equal to the sheet spacing of IP. Liu [17] offered another way to develop a computational model by considering IP as resulting from repeated competition between the carbide pinning force and transformation driving force. Although the carbon enrichment in γ was involved in Liu's model, it is noted that his results did not provide clear information about the relation between sheet spacing and carbon enrichment during $\gamma \rightarrow \alpha$ transformation. In addition to these numerical models, Lagneborg and Zajac [14] proposed another model addressing the effects of the nature of interface, diffusion mechanisms and composition dependence on the sheet spacing of IP. Recently, the present authors proposed a superledge model to predict IP characteristics by explicitly taking into account the thermodynamics and kinetics of α and carbide precipitation [24]. The effect of carbide precipitation on the α/γ interface controls sheet spacing and other characteristic features of IP.

Even though these models were developed from different considerations, they all show good agreement with the experimental results, and the temperature dependence of sheet spacing is correctly accounted for. It should be noted that these models are proposed to describe the idealized microstructure of IP, which means that carbides are well aligned on the interface. But none considers the curved sheets of IP and the possibility of CF. Indeed, as carbon or alloying element additions are increased, another carbide aggregate occurs: CF. The detailed formation mechanism of CF in alloyed steels is not yet clarified. Edmonds [5] first proposed a schematic model to compare the basic difference between CF and IP and concluded that the volume fraction of CF could be promoted by increasing Mn addition. In his view, the CF would like to form at higher transformation temperatures, because the carbide habit plane need not be as parallel to the interface. Barbacki and Honeycombe [25] carried out a series of isothermal transformations to explain the temperature dependence on the determination of carbide morphology in Mo and V alloyed steels. They pointed out that the VC fiber would actually like to form at a lower transformation, which contradicts the claims of Edmonds. In general, the nature of