Interphase Precipitation of Nano-sized Alloy Carbides in Low Carbon Steels

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論文内容要約

When low-alloy low-carbon steels containing strong carbide-forming alloying elements (M), e.g. Nb, Ti or V, are transformed from austenite (γ) into ferrite (α), alloy carbides (MC) are precipitated in sheets as a result of periodic nucleation at migrating α/γ interface, which is called interphase precipitation. Due to its excellent contribution to strength accompanied by reasonable formability, nano-sized MC formed through interphase precipitation has been recently used to strengthen low carbon steels especially for automotive application.

In order to improve mechanical properties of interphase precipitation strengthened steels, microstructural control on the dispersion of MC interphase precipitates is of great importance. Although the effects of transformation temperature and steel composition on the dispersion of MC and resultant strengthening have been widely investigated in literatures, the separate effects of α/γ interphase boundary characters, including interfacial coherency, interfacial migration rate and interfacial supersaturation, still remain unclear yet. Therefore, different from the previous studies, the effects of α/γ interphase boundary characters on the dispersion of MC formed by interphase precipitation were focused in the present study and systematically investigated mainly by using three-dimensional atom probe (3DAP). Based on the experimental results, the dominating factors on its dispersion were further discussed.

A series of M-added alloys with different amount of single and multiple M additions (V: 0.1 ~ 1.3mass%; Nb: 0.05 ~ 0.1mass%; Ti: 0.05 ~ 0.2mass%) were used in this study. All the homogenized alloys were austenitized at first to dissolve all the added M and then isothermally transformed at different temperatures from 873K to 1023K for various times, followed by water quenching. Afterwards, the microstructure was characterized by using optical microscopy (OM), scanning electron microscopy (SEM) with electron backscatter diffraction (EBSD) and transmission electron microscopy (TEM). 3DAP whose specimens were prepared by using focused ion beam (FIB) was used to quantify the dispersion of MC formed under various conditions. The resultant precipitation strengthening by MC interphase precipitation was further evaluated through Vickers hardness and nanoindentation measurements.

In chapter 3, the effects of interfacial coherency as evaluated by using α/γ orientation relationship (OR) were investigated. Based on α/γ OR analyses through EBSD measurement, it was found that as α/γ OR deviates from the exact Kurdjumov-Sachs

(K-S) OR, the formation of VC interphase precipitation is promoted with the reduction in interfacial coherency, accompanied by larger precipitation strengthening and higher resultant hardness of α grains. Such promotion was confirmed to be partly due to severer segregation of V at α/γ interface without holding K-S OR.

The effects of interfacial coherency and interfacial supersaturation as evaluated by using α growth rate and driving force for precipitation were investigated from chapter 4 to chapter 6.

In chapter 4, the effects of transformation temperature, V and C contents were investigated. VC interphase precipitation becomes finer by lowering the transformation temperature or increasing the V content, but remains almost unchanged by increasing the C content. Compared with α growth rate, the dispersion of VC interphase precipitates shows better correlations with driving force for precipitation calculated by using the α/γ interfacial concentration under local equilibrium.

In chapter 5, the effects of non carbide-forming alloying elements including Mn, Si and N contents were investigated. Lower Mn, higher Si and higher N contents slightly refines the dispersion of VC interphase precipitates, although such refinement is relatively small as compared with that caused by decreasing the transformation temperature. Further analyses reveal that the dispersion is dominantly determined by driving force for precipitation, while α growth rate only plays a minor role on interphase precipitation.

In chapter 6, VC, NbC and TiC formed by interphase precipitation were compared under the same condition by considering the interfacial supersaturation. With similar amount of M addition, NbC and TiC interphase precipitates are more finely dispersed than VC due to their larger driving force for precipitation, resulting in higher hardness of α grains. Consistently with the case of V, finer dispersion can also be obtained by increasing the Nb and Ti additions, although much larger driving force is necessary to obtain similar number density of NbC and TiC as VC. On the other hand, inter-soluble MC precipitates with homogeneous distribution of M atoms were found to be formed in the V-Nb and V-Ti multiple-added alloys, whose dispersion tends to fall between each single-added case.

In chapter 7, the dominating factors on the dispersion of MC interphase precipitates were discussed. By measuring the remained M content in α, the remained driving force for precipitation after interphase precipitation was calculated. With remained driving force, the average radius of MC interphase precipitates observed in this study was found to follow Gibbs-Thomson (G-T) effects with different α/MC interfacial energies for VC, NbC and TiC, respectively. In addition, remained driving force was almost proportional to the initial one. With certain volume fraction and radius, the number density of MC interphase precipitates becomes a function of driving force for precipitation, bulk M content and α/MC interfacial energy.

To obtain larger precipitation strengthening by finer dispersion of MC interphase precipitates, the necessary conditions can be summarized as larger driving force for precipitation, more amount of M addition and lower α/MC interfacial energy.