Dissolution of Nb(C,N) and (Ti,V)N in the Coarse-Grained Heat-Affected Zone of Electric Resistance Welded X65 Line Pipe

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Nb-rich and Ti/V-rich precipitates were introduced into the X65 linepipe *via* thermomechanical controlled processing. Their dissolution kinetics were investigated in the coarse-grained heat-affected zone after electric resistance welding. Nb-rich precipitates were found to dissolve completely, whereas Ti/V-rich precipitates were found to dissolve partially, because of slower dissolution kinetics. A complete dissolution of Nb-rich precipitates was associated with significant austenite grain coarsening, which promoted bainite as a quench product, which might have reduced the impact toughness.

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ELECTRIC resistance welding (ERW) is commonly used to manufacture line pipes for oil and gas transportation.[1] Recently, ERW line pipes with yield strength exceeding 358 MPa have been investigated for hydrogen service,[1–4] where an optimal balance between strength and toughness is critical. This balance is typically achieved through the addition of microalloying elements such as Nb, V, and Ti, combined with thermomechanical controlled processing (TMCP) to develop a fine ferrite grain structure dispersed with MX-type precipitates.[1,3–6] These precipitates, including NbC, TiN, and complex carbonitrides such as (Nb,Ti,V)(C,N), strengthen the steels by both precipitation hardening and grain refinement.[1,4,6] However, welding can significantly change the precipitate characteristics, leading to microstructural changes that degrade mechanical properties.[1,4,5,7,8] ERW involves a complex thermo-mechanical process characterized by rapid heating and cooling cycles combined with localized plastic compression deformation; the thermo-mechanical process sometimes degrades the microstructure and mechanical properties of the welded joint.[1,4,5] For example, ERW line pipes may fail to meet the minimum Charpy V-Notch (CVN) impact toughness of 27 J specified by API 5L.[1,4,8–13]

In line pipes, the behavior of microalloying precipitates during TMCP is well established; however, their evolution during ERW remains insufficiently explored.[4,5,11–13] Microalloying precipitates are categorized as strain-induced, interphase, or matrix-precipitated, depending on their formation stage.[14] Strain-induced Nb-rich carbides hinder recrystallization, suppressing Cube texture development and improving toughness,[15] while Ti additions supress the strain-induced NbC precipitation by epitaxial growth of NbC on pre-existing Ti-rich nitrides.[14] Microalloying precipitates' behavior is influenced by chemical composition, solubility, and thermal and deformation history.[4,5,15–17] Chung *et al.*[11] and Sisi *et al.*[13] linked the poor toughness of ERW line pipes to the dissolution of Nb and Ti-rich precipitates, which may promote grain coarsening, although definitive experimental evidence is lacking. Lee *et al.*[4] observed ~ 20–30 nm Ti,V(C,N) and NbC precipitates for ERW X70 steel after post-weld heat treatment (PWHT). Notably, the size and distribution of these precipitates differed from those in the base metal, leading the authors to suggest that original precipitates dissolved during ERW and subsequently re-precipitated during PWHT. However, direct experimental evidence was lacking. In contrast, Fazeli *et al.*[17] reported two distinct populations of Nb-rich precipitates, suggesting a more complex evolution mechanism. The literature thus highlights inconsistent observations, a lack of definitive experimental evidence, and an incomplete understanding of microalloying precipitate

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