

High Strain Capacity X60 Linepipe Steels with Superior Strain Aging Resistance

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Linepipe steels used for pipeline construction in arctic and seismically active environments are designed to withstand significant plastic strain in the longitudinal direction to ensure mechanical integrity. High uniform elongation and low yield-to-tensile strength ratio (YR) are part of the overall linepipe specification to ensure adequate strain capacity in these applications. These properties can be achieved in commercial-grade linepipe steels, e.g., X60, with a dual phase (DP) microstructure. However, upon short-duration exposures at relatively low temperatures during the application of fusion bonded epoxy (FBE) coating, a significant degradation in uniform elongation and YR is observed, a phenomenon commonly referred to as strain aging. This paper describes the mechanistic understanding of strain aging in dual phase X60 grade linepipe steels and the development of commercial-grade steels resistant to strain aging through modifications to manufacturing processes and steel chemistry.

INTRODUCTION

Oil and natural gas are critical energy sources for sustainable economic development in the foreseeable future. The major oil and natural gas fields in the world are often far removed from the markets. As a result, pipelines carrying these resources traverse long distances over land or under water. Some of the key pipeline projects on the horizon require a strain-based design approach where the pipeline must be capable of accommodating significant plastic strains. Examples of such projects are pipelines in seismically active areas or in arctic regions subject to frost-heave and thaw settlement cycles. Other examples include subsea pipelines that can experience strains due to displacement or bending caused by mud slides or thermal expansion effects. Accordingly, linepipe used for these environments requires adequate strain capacity, such as excellent uniform elongation and a low YR in the longitudinal direction of pipe to ensure mechanical integrity.

Dual-phase (DP) steels have a mixture of relatively soft ferrite phase and a relatively hard phase (e.g., martensite). The harder phase usually has more than one constituent (Koo et al., 1977a and b; Rashid et al., 1979). DP steels offer high uniform elongation and low YR, thus providing superior strain capacity (Nagorka et al., 1987; Sakaki et al., 1983; Jiang et al., 1995). For these

reasons, DP linepipe steel is attractive for installation in seismically active areas, in arctic regions subject to semi-permafrost conditions, or in other situations demanding high strain capacity.

The outer surfaces of the pipeline are typically coated with polymer for protection against corrosion, and fusion bonded epoxy (FBE) coating is generally used for this purpose. During the FBE coating process, the pipe is heated 5~8 min to a temperature in the 200-250°C range. The conventionally produced DP steel linepipe in the as-UOE condition exhibits excellent mechanical properties. However, heating of the linepipe to simulate the FBE coating process reveals degradation of uniform elongation and YR, and is associated with a steep increase in yield strength (Jin et al., 2003). Thus, it is important to understand significant changes in the key mechanical properties of the linepipe upon heating for the FBE coating.

Strain aging is manifested typically by an increase in strength and decrease in ductility upon heating at a relatively low temperature (200~400°C) after cold working. The strain aging phenomenon itself has been well studied and thought to result from the interaction between the stress field of dislocations and the strain field of solute atoms (Bergstrom et al., 1972).

The formation of solute atmospheres around dislocations, referred to as Cottrell atmospheres, pins the dislocations and restrains them from further movement on reloading (Mura et al., 1961). As a result, higher stress is required to break the dislocations away from the Cottrell atmospheres. These events lead to an increase of yield strength usually accompanied by the loss of ductility and rise of ductile-to-brittle transition temperature.

Current DP steel plate manufacture involves reheating to the austenite temperature range, rough rolling within the recrystallization temperature range, finish rolling within the non-recrystallization temperature range, air cooling to a temperature below Ar_3

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