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Formation mechanism and control methods of acicular ferrite in HSLA steels: A review

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ABSTRACT

High strength low alloy (HSLA) steels have been widely used in pipelines, power plant components, civil structures and so on, due to their outstanding mechanical properties as high strength and toughness, and excellent weldability. Multi-phase microstructures containing acicular ferrite or acicular ferrite dominated phase have been proved to possess good comprehensive properties in HSLA steels. This paper mainly focuses on the formation mechanisms and control methods of acicular ferrite in HSLA steels. Effect of austenitizing conditions, continuous cooling rate, and isothermal quenching time and temperature on acicular ferrite transformation was reviewed. Furthermore, the modified process to control the formation of multi-phase microstructures containing acicular ferrite, as intercritical heat treatments, step quenching treatments and thermo-mechanical controlled processing, was summarized. The favorable combination of mechanical properties can be achieved by these modified treatments.

1. Introduction

High strength low alloy (HSLA) steels were developed in the last century. As early as in 1934, HSLA steels were mentioned as low-alloy high-tensile steels [1]. In general, these steels contain up to 0.29 wt% C and small amounts of alloying elements, such as Mo, V, Nb, Ti etc., to obtain a minimum yield strength of 275 MPa under the as-rolled condition [2,3]. Through microalloying technique, HSLA steels are strengthened by precipitation hardening, solid solution strengthening and grain refinement strengthening [3–6]. HSLA steels have received more and more attention for their outstanding mechanical properties as high strength and toughness, and good performance-cost ratio [3,7,8]. Furthermore, addition of low C contents and controlling of alloying elements in HSLA steels can provide the desirable weldability [9–12]. Owing to their superior comprehensive properties, HSLA steels are widely applied in pipeline operators, automotive sector, navy vessels and nuclear fission power plant components, etc. [5,13–15].

Depending on the alloy compositions and processing parameters, the microstructures of HSLA steels may be composed of polygonal ferrite, pearlite, granular bainite, acicular ferrite and martensite [2,14,16,17]. Acicular ferrite dominated microstructure is one of the most attractive candidate microstructures for the high tensile strength, excellent impact toughness, as well as good weldability [18–20]. Furthermore, it has been recognized that the multi-phase microstructure with "soft" ferrite/pearlite and "hard" acicular ferrite/martensite can achieve a good combination of mechanical properties [21–23]. The acicular ferrite structure presents a highly sub-structured non-equiaxed phase with high density tangled dislocations pinned by fine carbonitride particles [24,25]. Besides, the fine carbonitride particles and M/A (martensite/austenite) islands can be observed inside acicular ferrite, providing a significant strengthening effect for HSLA steels [26,27]. The microstructure features and strengthening mechanisms of acicular ferrite have been investigated extensively. At the same time, there are still some controversies and uncertainties on the phase transformation kinetics and formation mechanisms.

In this paper, progresses in research and understanding of acicular ferrite formation during continuous cooling and isothermal quenching after austenitizing have been reviewed. This involves the factors of austenitizing conditions, continuous cooling rate, and isothermal quenching time and temperature that influence the acicular ferrite formation. On this basis, control methods of multi-phase microstructure containing acicular ferrite through the modified treatments, such as intercritical heat treatments, step

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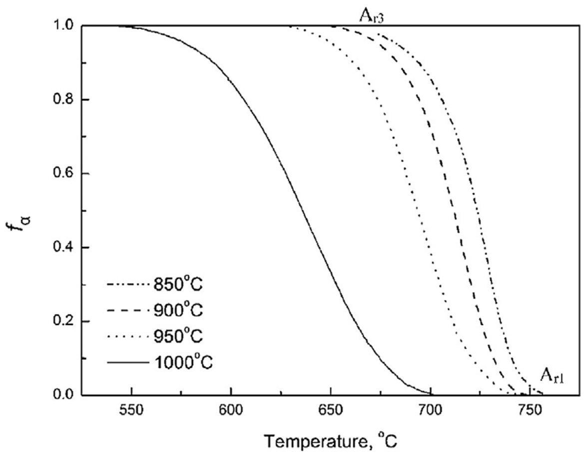

Fig. 1. Phase transformation fractions, determined by dilatometric measurements, as a function of temperature during continuous cooling, in the X65 pipeline steel specimens austenitized at the different temperatures from 850 °C to 1000 °C [28].

quenching treatments and thermo-mechanical controlled processing, were summarized.

2. Formation mechanism of acicular ferrite during heat treatment

2.1. Effect of austenitizing conditions on the acicular ferrite formation

It is generally acknowledged that austenization is the first step of heat treatment for many steels especially for HSLA steels. This would play a critical role in the final microstructures and thus resultant mechanical properties of steels. Additionally, austenization parameters have significant influence on the possibly subsequent quenching-tempering treatment, rolling or thermo-mechanical controlled processing (TMCP). Austenization conditions affect the prior austenitic grain size, coarsening and/or precipitate dissolution, and homogeneity of alloy elements distribution. These factors influence the transformation kinetics of austenite-acicular ferrite during cooling after austenization.

Effect of austenitizing temperature, in the range of 850–1000 °C, on acicular ferrite transformation in X65 HSLA pipeline steel was investigated [28]. As shown in Fig. 1, the starting and finishing temperatures for phase transformation during continuous cooling, namely A_{r1} and A_{r3} respectively, were both decreased with increasing the austenization temperature. This result suggests that increase of austenitizing improves the stability of austenite during cooling, and thus delays the decomposition of austenite. The decomposition products of austenite in X65 steel are mainly composed of polygonal ferrite, pearlite, acicular ferrite, etc. [29]. Increase of austenitizing temperature promotes formation of acicular ferrite and hinders formation of pearlite and polygonal ferrite (see Fig. 2). Higher austenitizing temperature brings about more sufficient dissolution of carbide forming elements as Nb, V and Ti, as well as more sufficient homogenization in austenite [30]. Generally speaking, the dissolved alloy elements would improve the stability of the metastable austenite [31]. Thus, decomposition of austenite is retarded to the lower temperature, which is also confirmed in Fig. 1. As a diffusionless reaction [32], acicular ferrite transformation is more likely to happen at the relatively low temperature, rather than the diffusion-controlled pearlite or polygonal ferrite transformation [33], since the diffusion rate of atoms is reduced with decreasing temperature.

Actually, a number of researches indicate that the second phase particles would provide the nucleation sites and facilitate acicular ferrite transformation [34–37]. It is generally recognized that acicular ferrite preferentially nucleates at the non-metallic inclusions [38], which is common in the weld metals. This is why acicular ferrite was always associated with weldments [36,38–40]. In addition to non-metallic inclusions formed during welding, the oxide and sulfide inclusions formed during steelmaking, and

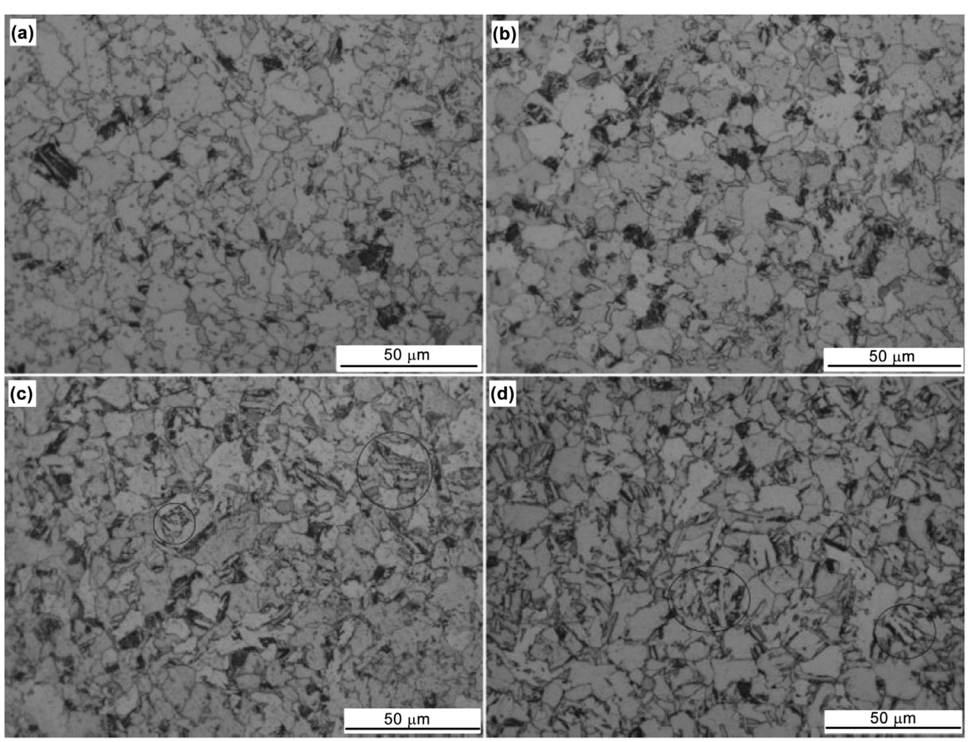

Fig. 2. Optical micrographs of X65 pipeline steel specimens after continuous cooling, with the different austenitizing temperatures as: (a) 850 °C, (b) 900 °C, (c) 950 °C and (d) 1000 °C [28].