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Effects of high-temperature deformation and cooling process on the microstructure and mechanical properties of an ultrahigh-strength pearlite steel

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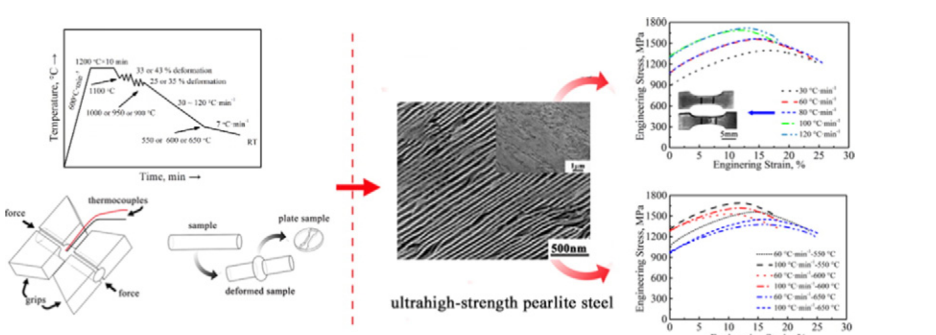
HIGHLIGHTS

- The effects of high-temperature deformation and cooling process on the microstructures and mechanical properties of a pearlite steel were researched.
- A new pearlite steel containing high Cr and high Si was obtained.
- A fully pearlite microstructure with an interlamellar spacing of approximately 100 nm was obtained.
- A full pearlite steel with a hardness of HRC50, a tensile strength of 1715 MPa and an elongation of 18% can be obtained.

GRAPHICAL ABSTRACT



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ABSTRACT

In this study, a new type of pearlite steel, 80CrSiV, is designed and the effects of the cooling rate, final cooling temperature, deformation temperature and level of deformation on the microstructures and mechanical properties of the steel are determined through thermal simulation, scanning electron microscopy, transmission electron microscopy, hardness and tensile tests. Results show that the microstructures and mechanical properties of the steel are significantly affected by the cooling rate after deformation and the final cooling temperature but are only slightly affected by the deformation temperature and level of deformation. A full pearlite microstructure with a hardness of HRC50.3, a tensile strength of 1715 MPa and an elongation not less than 17.9% can be obtained under the condition of a cooling rate of 120 °C·min^{-1} and a final cooling temperature of 550 °C.

1. Introduction

Pearlite steels with high strength, excellent wear resistance and fatigue failure resistance are used in high-strength steel wires, rails and so on [1–3]. The mechanical properties of pearlite are controlled by the microstructures, especially the pearlite interlamellar spacing and pearlite colony size [4–7]. Hyzak et al. [4] studied the relationships between the microstructures and the mechanical properties of pearlite and found that refining the interlamellar spacing and austenite grain size effectively enhanced the strength and fracture toughness of the steel. Refining the pearlite interlamellar spacing from 0.35 μm to 0.10 μm increases the pearlite rail rolling contact fatigue life and wear resistance by 29% and 30%, respectively; and also, increasing the volume of cementite from 41% to 50% can improve the above properties by 6.5%

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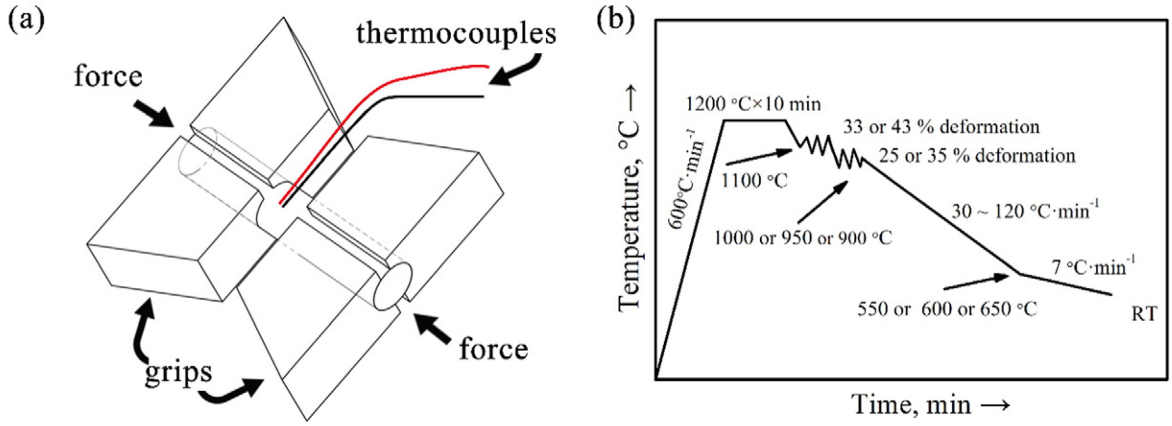

Fig. 1. Sketches: (a) deformation test principle for the Gleeble3800 equipment; (b) hot deformation and the subsequent cooling process for the steel.

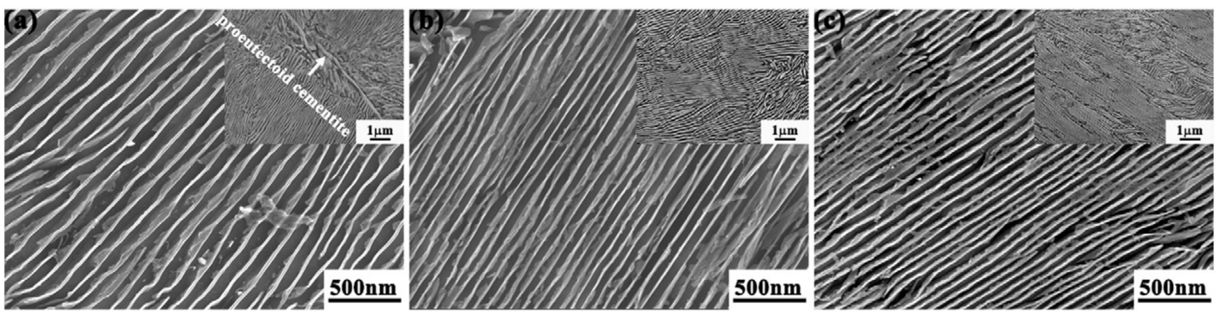

Fig. 2. SEM images of 80CrSiV steel cooled at different cooling rates: (a) 30 °C·min^{-1}; (b) 80 °C·min^{-1}; (c) 120 °C·min^{-1}.

and 4.3%, respectively [8]. The refinement of pearlite interlamellar spacing and the increase in carbon content can improve the hardness and work hardening behaviour of rolling wear, thereby prolonging the service life of pearlite rails [9]. However, when the carbon content increases and exceeds that of eutectoid steel, pre-eutectoid cementite networks precipitate at the prior austenite grain boundaries, which significantly decrease the ductility and toughness, even though increases the strength of pearlite steel [10].

Aside from the refinement of pearlite interlamellar spacing, solution strengthening and precipitation strengthening can also effectively enhance the strength of pearlite steels. Alloying elements such as Si, Mn and Cr not only exhibit a strong solution strengthening effect but also refine pearlite interlamellar spacing. Si does not solute in cementite, thus, the formation of cementite is controlled by the diffusion of Si into ferrite. Therefore, the addition of Si can effectively inhibit the formation of pro-eutectoid cementite [11–13]. At present, the pearlite steels mainly containing Mn and Si are studied, while the alloy of Cr is small or without added [14,15]. However, Tashiro et al. [16] indicated that Cr shows a stronger effect on the refinement of pearlite interlamellar spacing than that of Mn and Si. V precipitates in ferrite in a form of V (C, N), which improves the strength and hardness of pearlite steels [17]. In addition, V (C, N) can precipitate at the prior austenite grain boundaries of hypereutectoid steels inhibiting the precipitation of the continuous cementite networks at the grain boundaries [18,19]. Moreover, the precipitation of V (C, N) can be regulated via controlling the cooling rate after hot deformation to reach an aim of high hardness. Besides, the addition of N also can increase the amount of V (C, N) and further increase the hardness of V containing steel [20].

A lot of researches have demonstrated that hot deformation refined the austenite grain size, and the acceleration of cooling rate after hot deformation obviously refined pearlite interlamellar spacing, thereby improved the mechanical properties of steels [17]. During deformation in the recrystallization region, coarse austenite is refined by recrystallization, which consequently increases the area of grain boundaries; in the non-recrystallization region, austenite grains are elongated and form deformation bands. During cooling, pearlite nucleates at austenite grain boundaries and deformation bands, which promote the transformation from austenite to pearlite [21]. Increasing the cooling rate can improve the degree of undercooling and thus enhance the driving force of the phase transformation. Decreasing in pearlite transformation temperature slows down the diffusion of carbon atoms and decreases the growth rate of pearlite. Therefore, the combination of hot deformation, accelerating the cooling rate and decreasing the pearlite transformation temperature can effectively refine pearlite interlamellar spacing [21,22].

In this study, a novel type of hypereutectoid pearlite steel, 80CrSiV, containing high Cr, high Si and trace V is designed, and the effects of

Table 1
Mechanical properties and pearlite interlamellar spacing of the steel at different cooling rates.

CR (°C·min^{-1})	FCT (°C)	H (HRC)	UTS (MPa)	EL (%)	AR (%)	λ (nm)
30	550	43.8 ± 0.4	1413 ± 8	24.3 ± 2.8	24.1 ± 1.2	157 ± 6
60		46.2 ± 0.5	1560 ± 4	23.7 ± 0.8	28.5 ± 1.8	125 ± 6
80		47.0 ± 0.4	1575 ± 8	25.5 ± 0.6	29.7 ± 2.2	115 ± 5
100		49.3 ± 0.3	1686 ± 7	18.2 ± 1.5	22.1 ± 3.2	99 ± 3
120		50.3 ± 0.3	1715 ± 3	17.9 ± 2.2	16.6 ± 4.5	97 ± 3

CR: cooling rate, FCT: final cooling temperature, H: hardness, UTS: ultimate tensile strength, EL: total elongation, AR: area reduction, λ: perlite interlamellar spacing.