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Effect of vanadium on the high-cycle fatigue fracture properties of medium-carbon microalloyed steel for fracture splitting connecting rod

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ABSTRACT

The present investigation effort was made to study the effect of V up to 0.45% on the high-cycle fatigue properties of medium-carbon microalloyed (MA) steel 37MnSiVS, for the development of new crackable MA forging steel with excellent fatigue properties. The results show that the amount of V(C,N) precipitates increases with increasing V content and most of the precipitates are less than 5 nm. Owing to the significant precipitation strengthening effect of these nanosized particles, the hardness increase of ferrite with increasing V content is higher than that of pearlite and accordingly a decrease of pearlite/ferrite hardness ratio. Therefore, both fatigue strength and fatigue strength ratio increase with increasing V content and excellent fatigue properties could be obtained when V content is higher than about 0.28%. The fatigue crack growth (FCG) behavior is similar for all the three 37MnSiVS samples with an exponent $m \approx 3.5$. It is concluded that V can improve the fatigue properties of ferrite–pearlite steel mainly through precipitation strengthening and therefore it is anticipated that MA steel's fatigue property could be further improved as well as more fine V(C,N) particles be obtained.

1. Introduction

In today's automotive industry products must meet increasingly higher performance requirements while the production cost must be increasing lower. The connecting rod is one of the engine's core components and its quality and processing technology has been gaining great intention. The fracture splitting technology of connecting rod is an innovative processing technique that was developed in the 1990s [1]. Compared with the traditional method, the process owns the advantages of greatly improving product quality and production efficiency and significantly reducing cost and energy [2–4]. Therefore, the technology has been studied and applied extensively word widely.

In general, the material of connecting rod is a major factor that influences the fracture splitting process. The material not only affects connecting rod's mechanical properties such as rigidity, hardness, tensile and fatigue strength, but also directly influences fracture splitting ability and cleavage surface quality. The material suitable for fracture splitting connecting rod should have the following properties: (1) little deformation in fracture splitting; (2) good intensity; (3) proper brittleness; (4) good machinability [1]. At present, the materials that can be used to make fracture splitting connecting rod include power metallurgy material, malleable iron, nodular cast iron and high-carbon forging steel, etc. Among them, crackable high-carbon forging steel C70S6 based on conventional high-carbon pearlite steel SAE1070 was widely used, which shows a cleavage fracture surface and this is similar to that of power forged materials but is much cheaper [1,3–9].

It is well known that fatigue strength is the most significant factor (i.e. design driving factor) in the design and optimization of the connecting rod [6]. The fatigue strength of high-carbon forging steel C70S6 is higher than that of hot formed power metal [3], however, its fatigue strength is lower than that of conventional medium-carbon microalloyed (MA) forging steels such as 38MnVS at same strength level, which limits its further applications [9,10]. But it is impossible to use conventional medium-carbon MA steels to fabricate fracture splitting connecting rod because there is too much ductility and plastic deformation caused by fracture splitting pressure for the presence of considerable amount of soft and ductile phase of ferrite [1,11,12]. Plastic deformation does not permit the cap and rod accurately rejoining when assembled. The smaller the deformation, the better the brittle cleavage facture surfaces fit for each other. Therefore, there has been increasing studies for the

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development of crackable medium-carbon MA steels to fabricate fracture splitting connecting rod with improved fatigue properties [1,12–15].

One effective method to gain lower ductility is to strengthen the soft phase of ferrite through solid solution strengthening and precipitation strengthening, such as increasing the content of Si, P and V elements [1,12–15]. The precipitation strengthening effect of the carbonitride of V is more significant than other microalloying elements such as Nb and Ti after post-forging controlled cooling, and our previous study has confirmed that V can improve the fatigue property of ferrite–pearlite steel mainly through precipitation strengthening mechanism [16]. The normal addition of V is less than 0.15% in conventional medium-carbon MA forging steels. Therefore, the objective of this investigation is to study the effect of even higher addition of V up to 0.45% on the fatigue properties of medium-carbon MA steel 37MnSiVS, for the development of new crackable medium-carbon MA steel to fabricate fracture splitting connecting rod with significantly higher fatigue properties. Conventional medium-carbon MA steel 38MnVS was also used for comparison.

2. Materials and experimental procedure

The steels with different content of V, which were designated as V1, V2 and V3, were prepared in a 200-kg vacuum-induction furnace, and the ingots were heated to 1200–1220 °C for at least 1 h and then forged to rods with diameter of 18 mm and plates of 25 mm thickness and 70 mm width. The finish forging temperature was about 850–900 °C and then still air cooled. Commercial grade of conventional medium-carbon MA steel 38MnVS was also used in the form of 90 mm diameter round bar for comparison. The 90 mm round bar was reheated and forged to rods and plates as those of the above mentioned. The chemical compositions of the tested steels are given in Table 1. Smooth round bar specimens (Fig. 1), which were used to evaluate the fatigue strength in the rotating bar two-point bending fatigue tests, were prepared from the rod. Standard compact tension (C(T)) specimens for the fatigue crack growth (FCG) tests were machined from the plate in the *L*–*T* orientation and with a geometry shown in Fig. 2.

The surfaces of all the fatigue specimens were polished in the axial direction using No. 1000 abrasive papers after final finishing. Fatigue tests were conducted up to 10^7 cycles at different stress amplitudes at stress ratio $R = -1$ using PQ1-6 type rotating bar two-point bending fatigue testing machine. The rate of the stress cycling was 5000 rpm, and the tests were carried out in ambient laboratory atmosphere. The fatigue strength was figured out by the staircase method of at least six pairs in order to raise the confidence. The FCG tests were carried out on a MTS-880 universal testing machine with a frequency of 20 Hz. Before the test, 2–3 mm-long precrack was prepared at the root of the notch. The FCG rate $\mathrm{d}a/\mathrm{d}N$ was determined under $R = 0.1$. First, the relationship of the fatigue crack length a to the cycle numbers N_f was measured, then the data were treated to obtain the $\mathrm{d}a/\mathrm{d}N$–ΔK curve.

Optical microscope (OLYMPUS GX51) and scanning electron microscope (SEM, S-4300) were used for microstructural characterization. The specimens were etched with 3% nital solution, and the volume fraction of ferrite and pearlite interlamellar spacing were measured by using SISC IAS V8.0 software. Vickers hardness of the specimens were measured with a 5 kg load and Vickers microhardness of both the ferrite portion and the pearlite portion were also measured separately with a 5 g load, and the results were the average of at least 10 measurements. After fatigue tests, fracture surfaces were examined on an S-4300 type SEM.

Table 1
Chemical compositions of the tested steels (wt pct).

Steel	C	Si	Mn	P	S	Cr	V	Al	N
V1	0.37	0.80	1.05	0.033	0.086	0.17	0.15	0.021	0.018
V2	0.38	0.77	1.07	0.032	0.085	0.18	0.28	0.017	0.017
V3	0.38	0.74	1.03	0.033	0.088	0.18	0.45	0.024	0.020
38MnVS	0.37	0.18	1.32	0.008	0.061	0.14	0.12	0.018	0.011

The specimens for transmission electron microscope (TEM) were sliced into 0.5 mm thick plate and subsequently ground down to a thickness of about 50 μm. These foils were finally electropolished in a twin-jet electropolishing apparatus using a standard chromium trioxide-acetic acid solution. Thin foils were examined in an H-800 type TEM at an operating voltage of 200 kV to study precipitates. Physical–chemical phase analysis for precipitates was used to determining the amount of precipitation phase as well as the distribution of microalloying elements between the solid solution and the precipitation. A specimen of round bar with diameter of 6 mm and length of 100 mm was first undergone electrolytically extracted and then the extracted particles were identified using Philip APD-10 X-ray diffraction instrument. The particle size distribution of microalloying carbonitrides was determined using the small angle X-ray scattering method that can detect the particles within the range of 1–300 nm. More details about the experimental process see Ref. [17].

3. Results

3.1. Microstructures and mechanical properties

Figs. 3 and 4 show the optical and TEM micrographs of the tested steels as-forged and Table 2 summarizes the microstructural parameters and hardness of the steels. It is clear that the microstructures consist of polygonal pro-eutectoid ferrite and pearlite. With the increase of V content, the volume fraction of ferrite increases and the microstructure becomes finer and more uniform. These effects are generally associated with the influence of V on the formation of fine vanadium carbonitride V(C,N) particles (precipitation pining effect) and the suppression of grain boundary migration by being dissolved in the austenite (solute-drag effect) [18]. The formation of fine V(C,N) particles during forging not only lowers the carbon solution content in austenite but also promote the formation of intragranular ferrite, and therefore the increase of the volume fraction of ferrite with increasing V content. Also, the presence of fine V(C,N) particles during forging alters austenite grain growth and leads to fine ferrite–pearlite microstructure. As seen in Table 2, the increase of V content also reduces the pearlite interlamellar spacing. This result can be related to the influence of V on transformation temperature. As the solution of V in austenite could enhance the stability of austenite during cooling, and thus lowers the transformation temperature of austenite to pearlite. In general, the slow diffusivity at low temperature reduces the diffusion distance and consequently reduces the pearlite interlamellar spacing, and it was confirmed that interlamellar spacing is dependent on transformation temperature [19].

Also, according to the TEM observations (Fig. 4), two different precipitations such as random precipitation and interphase precipitation were identified, whereas most of the precipitations were random precipitated within pre-eutectoid ferrites and pearlitic ferrites (Fig. 4a, b, and d). Selected area diffraction pattern and energy dispersive spectroscopy (EDS) analyses of the precipitates revealed that the precipitate was V(C,N). The amount of V(C,N) particles increases with increasing V content.

As seen in Tables 2 and 3, although the volume fraction of ferrite increases with increasing V content, both hardness and strength increase with increasing V content mainly due to the precipitation