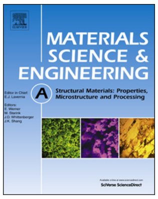
Materials Science & Engineering A 731 (2018) 360–368

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea



Effect of nitrogen contents on the microstructure and mechanical properties of V-Ti microalloyed steels for the forging of crankshafts

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ARTICLE INFO

Keywords:
Nitrogen
Mechanical properties
Microalloyed steel
Crankshafts
Intragranular ferrite

ABSTRACT

The microstructure and mechanical properties of vanadium-titanium microalloyed crankshaft steels with two different nitrogen concentrations were studied. The increasing nitrogen not content only refined the austenite grain size but also facilitated the formation of intragranular ferrite (IGF) idiomorphs. The V-Ti-N steel has a better combination of strength, plasticity and toughness than that of the V-Ti steel. Increasing the nitrogen content also facilitated the precipitation of V(C, N) particles in ferrite, which significantly strengthened it. This outcome remedied the strength reduction caused by the decrease in the pearlite volume fraction. The IGF idiomorphs can deform along with the outside pearlite compatibly and restrain the crack growth in pearlite while in tensile deformation. As a result, the plasticity is significantly improved from the increase of the IGF idiomorphs. Moreover, the effective grain size can be refined by the increase of the IGF idiomorphs, which improves the toughness.

1. Introduction

To eliminate the heat treatment process after forging automobile parts, the vanadium microalloyed steels for precipitation strengthening have been widely studied. It is well known that mechanical properties of steels can be improved by refining the austenite grain. However, it is difficult to implement sufficient deformation of austenite during the hot die forging of crankshafts. As a result, the final microstructure is usually coarse pearlite and network ferrite, which significantly reduce the mechanical properties of crankshafts. A similar problem also exists in the heat-affected zones of welded steels.

The intragranular ferrite (IGF) nucleated on particles in austenite has been used to refine the coarse microstructure of forged [1,2] or welded steels [3–5]. According to Dubé's classification of ferrite morphologies, the IGF can be divided into IGF plates and IGF idiomorphs. The IGF plates are usually formed in low carbon steels at low transformation temperatures. Miyamoto et al. [6] found that the plate morphology is closely related to the K-S relationship between the IGF and austenite. Moreover, many studies reported that the IGF plates were beneficial to obtain a better combination of strength and toughness [1,7,8]. On the other hand, the morphology of the IGF in V-N microalloyed steels for crankshaft forging is usually idiomorphic because of their high carbon content and low cooling rate. Ishikawa et al. [9] revealed that the V(C, N) particles on MnS inclusions were the main nucleation sites of IGF idiomorphs in V-N forged steels because of the Baker-Nutting orientation relationship ($(001)_{\alpha}//(001)_{V(C,\ N)}$, $[110]_{\alpha}//[100]_{V(C,\ N)}$) between the V(C, N) particles and ferrite. Furuhara et al. [10] found that the V(C, N) particles precipitating on MnS inclusions could hold incoherent orientation relationships with austenite and MnS inclusions simultaneously, which is beneficial to the nucleation of IGF idiomorphs. However, the effects of IGF idiomorphs on the mechanical properties have not been sufficiently studied.

In recent years, titanium has also been added to the vanadium microalloyed steels so that the (Ti, V)(C, N) particles could strongly inhibit austenite grain growth at high temperatures. Zhao et al. [11] found that the IGF idiomorphs nuclei of V-Ti-N microalloyed forged steels included (Ti, V)(C, N) particles on MnS inclusions. By increasing the nitrogen content in V-Ti forged steels, the precipitation of (Ti, V)(C, N) particles in the austenite matrix and on MnS inclusions may both be promoted. Therefore, besides the refinement of the austenite grain, the volume fraction of IGF idiomorphs may increase simultaneously.

The aim of the present work is to elucidate the effect of nitrogen on the microstructure and mechanical properties of a V-Ti microalloyed steel for crankshaft forging. The effects of IGF idiomorphs on the mechanical properties are also discussed.

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https://doi.org/10.1016/j.msea.2018.06.070
Received 22 March 2018; Received in revised form 13 June 2018; Accepted 17 June 2018
Available online 19 June 2018
0921-5093/

Table 1
Chemical compositions of the two steels (mass%).

Steels	C	Si	Mn	S	P	Cr	V	Ti	N
V-Ti	0.47	0.34	0.94	0.048	0.007	0.20	0.09	0.021	0.005
V-Ti-N	0.47	0.32	0.92	0.046	0.006	0.21	0.09	0.022	0.015

2. Experimental

2.1. Materials

The V-Ti microalloyed steels with two different nitrogen contents were chosen for the study, of which the chemical compositions are listed in Table 1. The two steels were smelted, casted and hot-rolled to Φ110 mm bars with the same technological parameters. The rolling bars were heated to 1200 °C with the rate of 5 °C/s, and were then die forged to crankshafts with a main journal diameter of 75 mm. The initial and finished forging temperatures were 1180 and 1100 °C, respectively. The 1–3# crankshafts were forged with the V-Ti steel, while the 4–6# crankshafts were forged with the V-Ti-N steel.

2.2. Mechanical properties

As is shown in Fig. 1, the standard samples were cut to test the mechanical properties of the crankshafts. The center of the samples is located at the 1/2 radius of the main journal.

To study the relationship between the mechanical properties and the microstructure, cylindrical samples with a diameter of 20 mm were cut at the 1/2 radius of the rolled bars to perform heat treatments. First, all the samples were heated to 1200 °C for 600 s and cooled to ambient at a rate of 0.3 °C/s. Then, the samples were heated to different temperatures (1000, 1100, 1200, 1300 °C) for 1800 s and cooled to ambient at a rate of 0.3 °C/s. One standard tensile sample and three standard impact samples were machined to test the mechanical properties.

2.3. Microstructural characterization

The metallographic samples were cut from the property samples and etched by 4% nital. For transmission electron microscope (TEM) analysis, thin foil specimens were prepared by mechanical thinning and ion thinning. For EBSD analysis, the samples were electrolytically polished in a solution of perchloric acid and alcohol. The EBSD maps were scanned using the TSL OIM Data Collection software with a step size of 0.3 μm, and analysed using the TSL OIM Analysis software. The EBSD effective grain size was calculated as the equivalent circle diameter related to the individual grain area. Tolerance angles of 15° were selected to recognize the grain boundary. To observe the original austenite grains, the samples were also water-quenched at 800 °C after heating at different temperatures for 1800 s. Then, the original austenite grains were etched in a supersaturation picric acid, and the mean austenite grain diameter was measured. Furthermore, the water-quenched samples were also made into TEM specimens using a carbon replication technique to observe the V-Ti particles before the ferrite phase transformation. This observation was performed with a ZEISS Axio Scope A1 optical microscope (OM), an FEI Quanta FEG 450 field emission scanning electron microscope (FESEM) and a JEM 2100HR transmission electron microscope. The composition of the particles was determined via energy dispersive spectroscopy analysis.

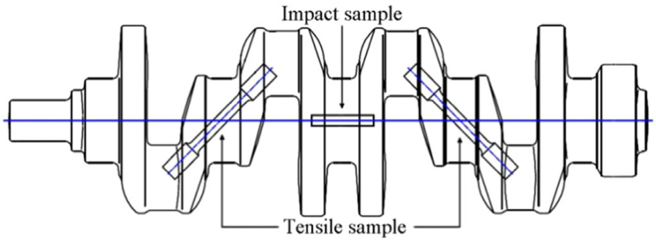

Fig. 1. The crankshaft samples to determine the mechanical properties.

3. Results and discussion

3.1. The effect of nitrogen content on the microstructure

The microstructure of the crankshafts samples is shown in Fig. 2. The ferrite mainly precipitated around the austenite grain boundary in the V-Ti steel, while IGF idiomorphs precipitated in the V-Ti-N steel. As shown in Fig. 3, as the nitrogen content increased from 0.0050% to 0.0150%, the mean austenite grain diameter decreased, and the volume fraction of the IGF idiomorphs increased significantly.

The original austenite grains, OM microstructure and IPF maps of heat-treated samples are shown in Figs. 4–6, respectively. The black lines in Fig. 6 represent the high misorientation boundaries of no less than 15°. For the V-Ti steels, the high misorientation mainly exists at the austenite grain boundaries. For the V-Ti-N steels, the austenite grains are refined significantly and the grain boundaries of the IGF idiomorphs also show high misorientation. The high misorientation boundaries can efficiently deflect or even inhibit the propagation of cleavage cracks and increase the crack propagation energy, which is beneficial to improve the toughness of steels [12–14].

The mean austenite grain diameter and the mean equivalent diameter recognized by 15° misorientation boundaries (MED_{15°) are shown in Fig. 7(a). After nitrogen addition, the formation of (Ti, V)(C, N) particles is considered to be promoted, and its dissolution temperature is also raised; thus, the austenite grain growth is inhabited because of the pinning effect. For the V-Ti steel, the MED_{15° is nearly same as the mean austenite grain diameter at 1000–1200 °C. However, the MED_{15° is much smaller than the mean austenite grain diameter at 1300 °C. As is shown in Figs. 5(d) and 6(d), part of the high misorientation also exists in the austenite grains and some IGF idiomorphs are formed because the austenite grains are too big after heating at 1300 °C. For the V-Ti-N steel, the MED_{15° is bigger than the mean austenite grain diameter at 1000 °C. As is shown in Figs. 4(e) and 5(e), some austenite grains are too small to retain the high misorientation boundaries during the phase transformation. At 1200 and 1300 °C, the MED_{15° is smaller than the mean austenite grain diameter possibly because several IGF idiomorphs are formed and the high misorientation boundaries increased. The relationship between the volume fraction of ferrite and mean austenite grain diameter is shown in Fig. 7(b). When the V-Ti-N steel is heated at 1000 °C, the austenite grains are too small to distinguish the grain boundary and intragranular ferrite, so the volume fraction of ferrite was not measured. With the increase of the austenite grain diameter, the austenite grain boundaries decrease. As a result, the grain boundary ferrite decreases, while the IGF idiomorphs increase. When the mean austenite grain diameters are same, the volume fraction of the IGF idiomorphs increases significantly with the nitrogen content increasing from 0.005% to 0.015%, but the volume fraction of the grain boundary ferrite shows little difference. This outcome indicates that the grain boundary ferrite is mainly controlled by the mean austenite grain diameter, while the nitrogen contents are the determining factor for the IGF idiomorph formation.

3.2. The effect of nitrogen content on IGF nucleation

According to our previous research [11], the nuclei of the IGF idiomorphs in the V-Ti-N steel are mainly (Ti, V)(C, N) particles on MnS inclusions, which is shown in Fig. 8.

The (Ti, V)(C, N) particles on the MnS inclusions are shown in Fig. 9 for when the V-Ti and V-Ti-N steels were cooled to 800 °C. The specimens were prepared by a carbon replication technique. The indentation of the carbon film shows the outline of the MnS inclusions. The size of