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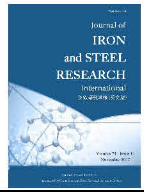

Mechanical properties of a microalloyed bainitic steel after hot forging and tempering

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ABSTRACT

Mechanical properties of a newly developed microalloyed bainitic steel were investigated after the hot forging, air cooling and tempering process. The microstructure of the as-forged bainitic steel mainly consists of granular bainite and ~20 vol. % martensite. The fraction of retained austenite remains unchanged until tempering at 200 ℃, above which it decreases significantly. The increase of tempering temperature leads to decreases of both ultimate tensile strength and total elongation but decreases of both yield strength and reduction of area. The maximum and minimum values of impact toughness were observed after tempering at around 200 and 400 ℃, respectively. These effects are mainly attributed to the decomposition of martensite/austenite constituents and the tempering effects in martensite. The tempering of the forged bainitic steel at around 200 ℃ results in an excellent combination of strength and toughness, which is comparable to that of the conventional quenched-and-tempered 40Cr steel. Therefore, low-tempering treatment coupled with post-forging residual stress relieving is a feasible method to further improve the mechanical properties of the bainitic forging steel.

1. Introduction

Since 1970s, the concept of microalloyed (MA) medium carbon forging steels with ferritic-pearlitic microstructure began to emerge in automobile industry and were applied to the production of automobile forging components such as crankshafts and connecting rods[1-3]. However, owing to its inherent cleavage fracture characteristic, the presence of pearlite limits the maximum obtainable toughness of this kind of steels, which thus has confined their applications mainly to components which do not require high toughness[4,5]. Therefore, numerous investigations have been conducted to improve the toughness of MA medium carbon ferritic-pearlitic forging steels for the purpose of critical applications to safety parts which require high degree of toughness[5-9].

Among these efforts, bainitic forging steels, which refer to steel grades having a composition adjusted to produce primarily a bainitic microstructure during the natural cooling that follows hot forging in this context, offer great possibilities as an alternative to quenched and tempered (Q&T) forging steels for highly stressed forged parts[10,11]. Early systematic studies by Matlock et al.[5] suggested that non-traditional bainitic steels with retained austenite (RA) offer a class of steels that exhibit significant opportunities for property control and optimization through alloying and processing. Later investigations further demonstrated that bainitic steels with low carbon content are good alternatives to Q&T forging steels for safety parts in cars and trucks with their strength and ductility values lying above comparable commercial steel grades[10-12]. With the rapid development of modern automobile industry, higher strength and toughness forging steels are demanded in order to lighten the structural parts as well as to satisfy the demand of the security concerns[3]. Therefore, Q&T forging steels are nowadays more and more successfully replaced by bainitic forging steels to manufacture front axle beams, steering arms and other automobile security parts[10-16].

Although direct comparison of isothermal and continuous cooling strategies of bainitic transformation with respect to the final mechanical properties revealed that the former gives better results than

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the latter[10,17], it is however strongly suggested to apply a continuous cooling to get robust processing conditions for hot forging as well as low cost[11,13,14]. As variations in cooling rate or component dimension are to be expected as part of the normal production of forging components, unlike grades designed for a single production process (rails, pipes), bainitic forging steel grades should be designed to offer the least sensitivity to cooling rate[11]. However, a mixture of microstructures is often found in continuous cooling transformation (CCT) of commercial bainitic forging steels after hot forging, which ranges from an acicular, carbide-free morphology to one with a non-acicular appearance, consisting of ferrite matrix containing constituents of martensite/austenite (M/A) or granular bainite. Other constituents such as martensite, ferrite and pearlite also sometimes exist. The existence of brittle untempered martensite is usually detrimental to the mechanical properties of bainitic forging steels as well as the non-equilibrium microstructure. Moreover, tempering treatment is often used to relieve the residual stress of bainitic steel forgings[13]. Therefore, the variety of different bainitic morphologies needs an aligned thermal treatment after forging to obtain maximum performance[10,12]. Although there have already been several studies considering the tempering behavior of bainitic steels[18-22], there are few published data available concerning the effect of tempering treatment on mechanical properties of this kind of bainitic forging steels[13]. Therefore, in the current work, the influence of tempering on the microstructure and mechanical properties of a novel bainitic forging steel microalloyed with V and Ti was investigated, in an attempt of optimizing the mechanical properties as well as promoting the applications of this steel.

2. Experimental Procedure

2.1. Materials and specimen preparation

A novel V and Ti MA bainitic forging steel 25MnCrVTi was adopted in this study. One commercial heat of widely used Q&T forging steel 40Cr in the form of round bar with diameter of 65 mm was selected for comparison. The chemical compositions of the tested steels are listed in Table 1. The bainitic forging steel was cast into 39 kg ingot after melted in a vacuum-induction heating furnace with a capacity of 50 kg. The ingot was heated to 1200－1220 ℃ and held at this temperature for at least 1 h, and then it was press forged to rods with diameter of 18 mm. The finish forging temperature was controlled at about 850 ℃ followed by air cooling to room temperature. The as-received 40Cr steel round bar with diameter of 65 mm was heated and hot forged to rods also with diameter of 18 mm.

Standard smooth tensile specimens (gauge length of 25 mm and diameter of 5 mm) and Charpy U-notch impact specimens (10 mm × 10 mm × 55 mm) were machined in the longitudinal direction of the rods. To investigate the influence of tempering treatment, the specimens of the bainitic forging steel were tempered at 200, 300, 400 and 500 ℃ for 120 min, respectively. Specimens of the 40Cr steel were austenitized at 860 ℃ for 30 min, oil quenched and then tempered at 510 ℃ for 120 min to obtain high-temperature tempered martensite microstructure with similar tensile strength level to that of the as-forged bainitic forging steel. Cylindrical dilatometer specimens (4 mm in diameter and 10 mm in height) for CCT curve measurement were cut from half radius of the as-forged bainitic steel rods and had the long axis parallel to the rod axis.

Table 1
Chemical compositions of tested steels (wt. %)

Steel	C	Si	Mn	P	S	Cr	V	Ti	Al	N
MB2	0.25	0.37	1.96	0.007	0.021	0.48	0.11	0.03	0.029	0.014
40Cr	0.43	0.27	0.74	0.013	0.005	0.90	—	—	0.022	0.006

2.2. Microstructural and mechanical evaluation

Optical microscope (OM, Zeiss Axio Scope A1) and scanning electron microscope (SEM, Zeiss EVO18) were used for microstructures observation after standard metallographic grinding and polishing and finally etching in 3 vol. % nital solution. The volume fraction of RA was measured by D/max 2500V X-ray diffraction (XRD) instrument using CuKα radiation. Foils for transmission electron microscope (TEM) were sliced into 0.5 mm in thickness and mechanically ground down to about 50 μm thick before finally electro-polished in a twin-jet electro-polishing apparatus using a solution of standard chromium trioxide-acetic acid solution. Thin foils were examined in a TEM (Hitachi H-800) at an operating voltage of 200 kV. Dilatometer specimens were heated to 900 ℃ at a rate of 10 ℃/s, then held for 5 min, and finally cooled to room temperature at different linear cooling rates ranging from 0.06 ℃/s to 43 ℃/s using a Bähr D805L dilatometer. The CCT diagram was constructed after determining the critical transformation