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Effect of vanadium on dynamic continuous cooling transformation behavior of medium-carbon forging steels

Wei-jun Hui[1,*], Na Xiao[1], Xiao-li Zhao[1], Yong-jian Zhang[1], Yu-feng Wu[2]

[1] School of Mechanical, Electronic and Control Engineering, Beijing Jiaotong University, Beijing 100044, China

[2] Faculty of Materials Science and Engineering, Kunming University of Science and Technology, Kunming 650093, Yunnan, China

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ABSTRACT

Dynamic continuous cooling transformation (CCT) behavior of medium-carbon forging steels microalloyed with different V contents up to 0.29% was investigated by means of dilatometric measurement, microstructural observation and hardness measurement. The results showed that the dynamic CCT diagrams were similar and the main difference was that the fields of the transformation products were shifted to the right side of the diagrams with the increase of V content, and this effect was more noticeable with an addition of 0.29% V. The A_{c1} and A_{c3} temperatures showed increasing trends with increasing V content, while the critical cooling rates decreased with increasing V content. The increase of V content resulted in significant increase of hardness and this tendency was enhanced with increasing cooling rate until the formation of acicular ferrite (AF). A promising approach of remarkably improving the toughness of ferritic-pearlitic medium-carbon forging steels with suitable V addition and the introduction of AF without notable penalty on its strength level was suggested.

1. Introduction

Recently, there have been increasing applications of microalloyed (MA) medium-carbon forging steels as substitutes for traditional quenched and tempered (Q&T) forging steels to manufacture a variety of automobile components. Eliminating the cost of post-forging heat treatment (quenching and high temperature tempering) is the main target for the introduction of this kind of steel[1,2]. The desired mechanical properties of forged components could be obtained through controlled cooling from forging temperature. Therefore, factors such as chemical compositions, cooling strategies and forging parameters have strong influences on the microstructural characteristics, and thus on the final mechanical properties of forgings made of this kind of steel[3-8].

It is well known that continuous cooling transformation (CCT) diagram is an excellent tool to study the influence of chemical composition and cooling rate on phase transformation products, which ultimately influence the mechanical properties, as it allows to identify the domain and boundary of each phase and/or constituent (ferrite, pearlite, bainite and martensite) as a function of cooling rate[9]. The construction of a CCT diagram is based firstly on dilatometric analysis complemented by both microstructure and hardness studies. The shape of a CCT diagram is very sensitive to the chemical compositions of the tested steel and the cooling rates used during processing[10,11]. In the case of MA medium-carbon forging steels, Mn and microalloying elements are generally present. The addition of Mn shifts the eutectoid point towards lower carbon concentration, lowers the phase transformation temperatures, and thus promotes pearlite formation and decreases the transformation speed of austenite to pearlite[12]. Mn also makes the proeutectoid ferrite curve of CCT diagrams move to the right, and greatly promotes the formation of intermediate transformation products such as bainite[13]. Furthermore, it is well known that the Mn addition increases the solubility of VC and VN in austenite, and thus enhances precipitation hardening effect[12]. There-

* Corresponding author. Prof., Ph.D.
E-mail address: *wjhui@bjtu.edu.cn* (*W. J. Hui*).

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fore, for MA ferrite-pearlite type forging steels, their Mn contents are usually lower than 1.5%, whereas for MA bainitic forging steels, those are enhanced to higher than 1.5%.

The main microalloying element in MA medium-carbon forging steels is V due to its strong and easily controllable precipitation hardening effect, which is primarily due to the relatively large solubility of its carbonitride V(C,N) in austenite at convenient heating temperature[1,11,12]. Fine V(C,N) particles could precipitate in both proeutectoid ferrite and pearlitic ferrite on continuous cooling during and/or after austenite-ferrite transformation[2,5]. There is still some disagreement in literature regarding the effect of V on the transformation behavior of MA steels. It is generally believed that V atoms segregate to austenite grain boundaries rendering them less effective as ferrite nucleation sites, thus increasing hardenability by suppressing ferrite-pearlite formation[5]. However, it is also believed that V actually does not suppress grain boundary reaction and even decreases hardenability[1,14]. Recent study of the authors has shown that ferrite fraction increases with increasing V content in as-forged 37MnSiVS steel[15], and further investigation also revealed that increasing V content significantly enhances the formation of acicular ferrite (AF) structure at a moderate cooling rate[16]. The results of the influence of reheating temperature and V content on the transformation behavior of medium-carbon forging steels suggest that V in solid solution promotes the formation of bainite[5]. It has also found that V(C,N) particles can act as preferential nucleation sites for bainite in V-MA medium-carbon steels, which thus facilitates bainite formation at faster cooling rates[17].

It should be noted that deformation also has a significant influence on the phase transformation of steels[13,18]. Therefore, it is not enough only to know the static CCT diagrams which describe the transformation in non-deformed austenite of forging steels. Moreover, mainly due to its efficient precipitation hardening effect and significant improvement of fatigue properties of medium-carbon forging steels[15], there has been a tendency to further increase V content up to about 0.30%[19,20]. Therefore, the aim of the present study is to systematically investigate the influence of V content up to 0.30% on the dynamic CCT characteristics of medium-carbon forging steels. The hardness change and microstructural evolution with cooling rates have also been analyzed. The results will be beneficial to the practical application of controlled forging and cooling to the production of high performance forging components made of MA medium-carbon steels.

2. Materials and Experimental Procedure

Medium-carbon forging steels with different contents of V (0%, 0.10% and 0.29%), which were designated as D1, D2 and D3, were used in the present study. These steels were melted in a laboratory vacuum induction furnace and cast into 110 kg ingots. Table 1 shows the chemical compositions of the tested steels. These as-cast ingots were reheated to about 1250 ℃, held for at least 1 h, and finally press forged to bars (45 mm in diameter) followed by still air cooling. Cylindrical specimens (6 mm in diameter and 80 mm in height) were cut from half radius of the as-forged bars and had the long axis parallel to the bar axis.

Table 1
Chemical compositions of tested steels (mass%)

Steel	C	Si	Mn	P	S	Cr	V	Ti	Al	N	Fe
D1	0.41	0.42	1.25	0.015	0.041	0.16	—	0.017	0.029	0.022	Balance
D2	0.40	0.44	1.22	0.015	0.039	0.17	0.10	0.022	0.031	0.016	Balance
D3	0.40	0.44	1.26	0.017	0.042	0.18	0.29	0.027	0.031	0.017	Balance

The dynamic (with hot deformation) CCT diagrams were conducted on a Gleeble-3800 thermomechanical simulator. Thermocouples with a diameter of 0.2 mm were spot welded to the surface of the specimens at their middle length to record the temperature. Specimens were firstly reheated to 1220 ℃ at a constant heating rate of 10 ℃/s and held for 120 s, and then they were cooled at 5 ℃/s to deformation temperature 1100 ℃. To minimize temperature gradient, the specimens were kept at 1100 ℃ for 5 s. Then, the specimens were compressed to a true strain of 0.36 (reduction in height of 30%) at a nominal strain rate of 1 s^{-1} and finally cooled to room temperature at different linear cooling rates in the range of 0.03-41.50 ℃/s. These cooling rates were chosen as indicated by the static CCT diagram of medium-carbon forging steel with similar chemical composition[12], which were then controlled by the designed cooling pattern of the simulator system. Several specimens were directly quenched from deformation temperature in order to determine the initial austenite grain size. The dynamic CCT diagrams were constructed after determining the critical transformation temperatures complemented by microstructural observations and Vickers hardness measurements.

Specimens for optical microscopy (OM) were mechanically ground and polished, and then etched with