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Effects of Chromium, Vanadium and Austenite Deformation on Transformation Behaviors of High-strength Spring Steels

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Abstract: The phase transformation behavior during continuous cooling of high-strength spring steels containing different amounts of Cr was studied. Furthermore, the effects of combining Cr with V as well as austenite deformation on the transformation kinetics were investigated in the method of dilatometry and metallography hardness. The results showed that, with the increase of Cr, the pearlite transformation field was enlarged, the ferrite transformation field was narrowed, and the entire phase field shifted to the right. With the addition of V, the start transformation temperature of undercooling austenite (A_{r3}) was gradually increased, but the ferrite and pearlite transformation fields were not affected. Besides, the minimum critical cooling rate of martensitic transformation was also reduced. In addition, the dynamic continuous cooling transformation (CCT) curve moves to the top left compared with the static CCT curve. The transformed microstructures showed that the addition of V and the deformation not only refined the overall transformed microstructures but also reduced the lamellar spacing of pearlite. The alloying elements Cr and V promoted the Vickers hardness. However, the effect of Cr on the Vickers hardness of martensite was stronger and the influence of V on that of pearlite was stronger. Moreover, the Vickers hardness affected by the austenite deformation was more complex and strongly depended on the transformed microstructures.

Key words: spring steel; phase transformation; Chromium; deformation; microstructure

With the rapid development of high-speed railways, the amount of high-strength spring steels used in elastic rail clips (ERCs) for high-speed railways has been gradually increased. The ERC presents a quite complicated stress state in the course of service[1-3]. No residual plastic deformation is permissible even under heavy static or cyclic loads and springs must return to their original states after removal of external loads. Moreover, from the point of realistic use and economic considerations, a good combination of fatigue and corrosion resistance therefore becomes essential. In recent years, the very high fatigue resistance of several spring steels like Cr alloys[4], Si-Cr alloys[5-7] and Cr-V alloys[5-7] have been reported. And it is widely recognized that low Cu, Cr, Ni and Ti additions in weathering steels can improve the corrosion resistance with respect to plain carbon steel. Moreover, the ability of Cu and Cr in retarding the corrosion rate during drying step[8,9] and the role of Ti in the inhibition of akaganeite formation[10] have been reported. The beneficial effects of Cu and Cr may be attributed to their ability to inhibit the reduction of rust[11]. More recently for Cr-alloyed steels, the formation of a Cr-enriched goethite at the oxide/steel interface has been demonstrated[12].

Furthermore, micro-alloying technology has been widely developed in special steels. And part of the application is also realized in spring steels[13-16]. Particularly, Vanadium is the most important alloying element in medium carbon micro-alloyed steels. V carbon/nitride (VCN) particles promote precipitation strengthening effect in ferrite and pearlite[17]. V additions can be also beneficial to the toughness as

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a result of the preferential intragranular nucleation of acicular ferrite on VCN or VN particles[18,19]. These precipitates can also nucleate on existing TiN particles and oxides to form complex inclusions that serve as nucleation sites for ferrite，which helps to refine the microstructure[20-23]. Considering that the market price of niobium iron is more than 10 times expensive than titanium iron，in order to develop high-strength spring steel with low cost and high additional value，vanadium and titanium micro-alloyed spring steels are here designed.

Continued development of high-strength spring steels requires an understanding of their transformation behaviors and how those transformations are affected by alloying elements additions as well as austenite deformation. A continuous cooling transformation (CCT) diagram is a useful way of displaying the transformation behavior of a material as a function of thermo-mechanical control process (TMCP). In this paper，the continuous cooling transformation curves of high strength spring steel with different compositions were determined using Gleeble-3500 thermal mechanical simulator，Dil805 quenching and deformation dilatometer by dilatometry and metallography hardness method. The objects were to clarify the formations of microstructures of high-strength spring steels by investigating the effects of alloying elements additions and hot deformation on the CCT. The results will be beneficial to the practical application of TMCP and thermal treatments processing in the production of high performance spring steels.

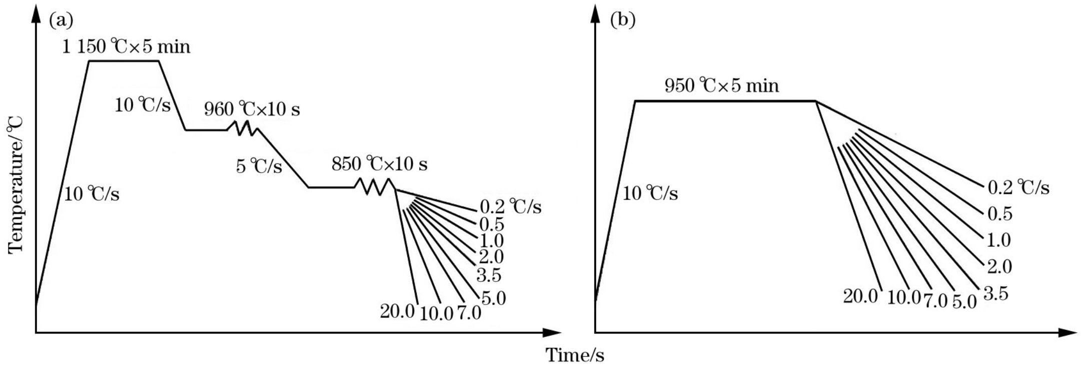
1 Experimental Procedure

The materials used in this work，i. e. four laboratory smelted medium carbon steels for spring application，were firstly prepared in a 25 kg vacuum induction melted furnace，subsequently the cast slabs were hot forged and homogenizing annealed. Specimens used in the deformed states (HSS，35Cr，35Cr+V and 85Cr+V) and undeformed state (85Cr+V) were machined from the forged rods. Chemical compositions of these four steels are listed in Table 1，identified as HSS (deformed)，35Cr (deformed)，35Cr+V (deformed)，and 85Cr+V (deformed and undeformed).

Table 1 Chemical compositions of tested steels mass%

Steel	C	Si	Mn	S	P	Cu	Ni	Cr	V	Ti	Fe
HSS	0.51	2.14	0.30	0.0047	0.0045	0.29	0.20	—	—	0.071	Balance
35Cr	0.50	1.84	0.35	0.0049	0.0045	0.25	0.28	0.33	—	0.095	Balance
35Cr+V	0.50	2.09	0.30	0.0048	0.0038	0.27	0.28	0.34	0.17	0.100	Balance
85Cr+V	0.51	2.04	0.31	0.0048	0.0035	0.30	0.28	0.86	0.17	0.076	Balance

Heat treatments were performed by using Gleeble-3500 thermal mechanical simulator and Dil805 quenching dilatometer in an inert atmosphere of argon gas. Two heat treatment patterns were employed to simulate the hot deformation and continuous cooling schedules (Fig. 1). Treatment (a) was a hot deformation schedule; the specimens were firstly austenitized for 300 s at 1150 ℃，subsequently deformed by approximately 35% at 960 ℃ after cooling at 10 ℃/s from 1150 ℃，and then deformed by approximately 30% at 850 ℃ after cooling at 5 ℃/s from 960 ℃，and finally cooled at the constant cooling rates of 0.2，0.5，1，2，3.5，5，7，10 and 20 ℃/s，respectively. Treatment (b) was a undeformed schedule;



(a) Hot deformation schedule; (b) Continuous cooling schedule.

Fig. 1 Schematic diagrams of heat treatment procedures