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Calculation and Inspection of Alloy Design of Cr-W- Mo-V High Alloy Steel Addition Niobium for Machinery Knives

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Abstract

In this paper, the alloy design calculation and analysis of Cr-W-Mo-V alloy steel containing a micro-amount of Nb were reported detailedly, and the microstructure and technology properties of experimental steel applied to the copper brazing with quenching for machinery knives also were given laconically. The calculation and analysis by phase equilibrium thermodynamic method show that, the dissolution/precipitation temperature of MC carbide of the steel adding a small quantity of Nb is rising evidently, it is conducive to the preservation of undissolved thin carbides in the quenching temperature, and can reliably prevent the austenite grain size coarsening. In the high temperature zone the Nb content of MC carbide gradually is increasing and V content of MC carbide gradually is decreasing with temperature rising, as more than 1200℃ MC changes constitutionally into NbC. In the low temperature zone the V content of MC carbide gradually is increasing and the change of Nb content is very small with temperature reducing, as less than 900℃ MC changes constitutionally into VC. The suitable quenching temperature of the steel addition Nb is 1100~1150℃on the basis of hardness calculation and carbide phase calculation. When tempering at 540℃ after quenching at 1150℃, it can obtain high hardness of HRC64-65 in agreement with the alloy design calculation.

Keywords: Machinery Knife, Cr-W-Mo-V Steel, Addition Niobium, Alloy Design, Equilibrium Phase, Austenitic Composition, Carbide Refinement, Hardness Calculation, Heat Treatment, Microstructure

1 Introduction

The edge steels of machinery knives must have high hardness and wear resistance, and its microstructure must be very fine to ensure a high sharpness, high wear resistance and high impact toughness. On the basis of alloy design calculation by phase equilibrium thermodynamic method for Cr-W-Mo-V alloy tool steel[1,2], we successfully have calculated and designed of a suitable edge steel for manufacturing machinery knives by copper brazing with quenching, this steel is a high alloy medium-upper carbon steel containing a small quantity of Nb. When the steel contains a suitable amount of Cr-W-Mo-V, even if C content of 0.52~0.62/wt% the highest tempering hardness of secondary hardening after quenching can reach HRC64~65[3]. When adding small amounts of Nb the carbide in the steel can be further refined, and it will effectively prevent quenching austenite grain growth even if expanding quenching temperature range[4]. Therefore, as an edge steel of machinery knives it can implement copper brazing with quenching at higher heating temperature at the same time. This edge steel of machinery knives and its production technology have been applied to the Chinese invention patent[5]. In this paper, the alloy design calculation and analysis of Cr-W-Mo-V alloy steel containing a micro-amount of Nb were reported detailedly, and the microstructure and technology properties of experimental steel applied to the copper brazing with quenching for machinery knives also were given laconically, and the effect of micro Nb content on carbide refining and grain refinement of the steel also was discussed incidentally in depiction.

2 Composition of calculational steel and experimental steel

Alloy design of the Cr-W-Mo-V high alloy steel addition Nb is based on the requirements of manufacturing and performance for machinery knives. First a series of different components of calculational steels with different combination is selected, and then the main technical indicators of alloy design are calculated. The main technical indexes of this steel are quenching carbide size ≤1.5μm and undissolved carbide volume fraction 3%~5%, after quenching the highest tempering hardness of HRC64~65, and while brazing and quenching the heating temperature of 1140℃～1160℃. By the main technical parameters, the calculation results of calculational steels with different composition are analyzed carefully, and are selected finally to a proper composition of the steel. Above process of calculation and analysis is complex confoundedly. For concise paper topics, the final composition of calculational steel and an composition of experimental steel were listed in Table 1. From Table 1 can see that, it is a kind of Cr-W-Mo-V alloy steel adding a small quantity of Nb in which the Mo content is higher and the C content is medium-upper, but it can obtain very high hardness of secondary hardening[3]. In Table 1 the designed composition gives the melting composition range, and the calculational composition is accurate computed components in which of a same C content and alloy content but only Nb content of 0, 0.15 and 0.25 respectively, and the experimental composition is first melted composition by designed range.

TABLE 1 COMPOSITION OF THE CALCULATIONAL STEEL AND THE EXPERIMENTAL STEEL (*WT*%)

	C	Si	Mn	Cr	W	Mo	V	Nb	Ni
Designed	0.56-0.65	0.4-0.6	0.25-0.4	6.0-6.8	1.6-2.0	4.2-4.8	0.7-0.9	0.1-0.2	0.3-0.4
Calculational	0.62	0.48	0.38	6.40	1.80	4.50	0.80	0/0.15/0.25	0.35
Experimental	0.63	0.56	0.41	6.12	1.82	4.45	0.76	0.13	0.33

As a supplement, while optimization and selection the calculation results of tempering hardness and mole fraction of quenching undissolved carbide of seven constituent steels were listed in table 2. Can be seen from table 2, the compositions of 1-4 meets the requirements of the main technical indicators, that the tempering hardness of HRC64.2-65.2 is near in accordance with the technical requirements although the quenching hardness has difference. And the mole fraction of quenching undissolved carbides is 2.49%~3.45% converted into a volume fraction of about 3.92% ~ 5.52%, it effectively hampers austenite grain strong growth. The tempering hardness of 5-7 also is higher, but the difference of carbides mole fraction is greater too, apparently, some smaller is not conducive to refine austenite grain, and some bigger is not superior of the tempering hardness when copper brazing with quenching at high temperature 1150℃.

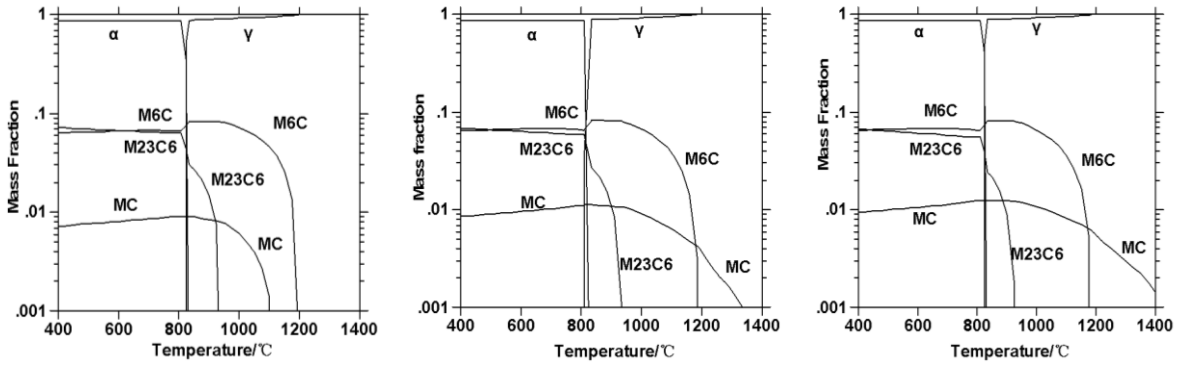
TABLE 2 COMPOSITIONAL HARDNESS AND CABIDE OF Cr-W-Mo-V STEELS WITH DIFFERENT COMPOSITIONS

No	Alloy composition/*wt*%									Quenched at 1150℃		Tempered
	C	Cr	W	Mo	V	Nb	Ni	Si	Mn	/HRC	carbide/mole%	/HRC
1	0.56	6.8	2.0	4.8	0.9	0.15	0.35	0.50	0.40	62.3	3.45	64.2
2	0.58	6.8	2.0	4.6	0.9	0.13	0.35	0.48	0.38	63.1	3.15	64.5
3	0.62	6.2	1.8	4.5	0.8	0.13	0.40	0.48	0.38	64.4	2.45	65.3
4	0.65	6.5	2.0	4.0	0.9	0.10	0.30	0.52	0.35	64.9	2.49	65.2
5	0.68	7.7	2.3	3.1	0.7	0.13	0.36	0.56	0.39	65.5	1.29	64.2
6	0.65	7.2	1.6	4.2	0.7	0.10	0.20	0.40	0.25	65.8	1.23	65.6
7	0.65	8.0	2.0	5.0	0.9	0.15	0.30	0.60	0.40	64.3	5.03	64.2

3 Microstructure calculation and analysis

Fig 1 is the equilibrium phase diagram of calculational steels with temperature change. Fig. 1 shows, M_6C and $M_{23}C_6$ carbides of three calculational steels with temperature change are similar, just the MC carbide was greatly affected. The quantity of MC carbide increases with the increasing of Nb content of the steels, therewith, the quantity of M_6C carbide also decreases correspondingly. When content of 0 Nb, the dissolution(or precipitation) temperature of MC carbide is about 1100℃(see Fig.1a); when the content of Nb is 0.15, the dissolution temperature of MC carbide is about 1320℃(see Fig.1b); when the content of Nb is 0.25, the dissolution temperature of MC carbide exceeds to 1400℃(see Fig.1c). While the steel adding a micro-amount of Nb the dissolution temperature will hoisted obviously,

it is conducive to the preservation of undissolved carbides in the higher quenching temperature and reliably prevents austenite grain size coarse too.



(a) 0Nb (b) 0.15Nb (c) 0.25Nb

FIG.1 EQUILIBRIUM PHASE DIAGRAM OF THE CALCULATIONAL STEELS WITH CHANGING TEMPERATURE

Fig 2 is a phase equilibrium thermodynamic diagram of longitudinal section of calculational steel containing 0.15Nb, the precipitation temperature of MC carbide is higher than that of M6C. Under L+δ→γ peritectic phase transition, the MC carbide is beginning to precipitation at once, and austenite crystallization will delayed as solute of Nb[6]. While lower content of C the δ+γ+MC three-phase region is wide or becomes four phases adding M6C, and while higher content of C the disappeared temperature of L phase decreases as well. Therefore, the C content in the steel are restricted, which exactly is the design requirements of the steel with high toughness.

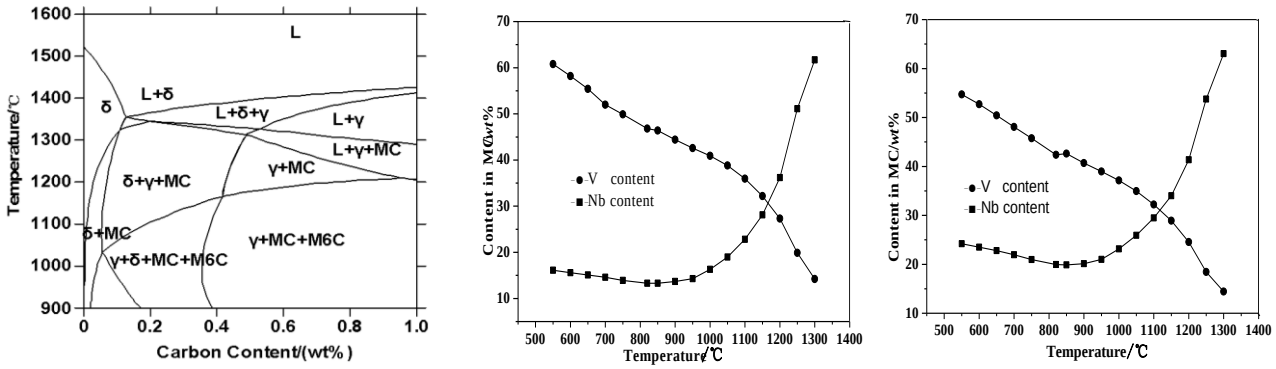


FIG.2 LONGITUDINAL SECTION DIAGRAM OF CALCULATIONAL STEEL WITH 0.15Nb

(a) 0.15 Nb (b) 0.25Nb

FIG.3 V AND Nb CANTENTS IN MC CARBIDE WITH TEMPERATURE

Fig.3a and Fig.3b are V and Nb contents in MC carbide of calculational steel containing 0.15 Nb and 0.25 Nb respectively. Can be seen from Fig.3, in high temperature zone the Nb content in MC carbide swiftly increases and V content in MC carbide swiftly decreases with temperature rise, while more than 1200℃ MC changes constitutionally into NbC. In low temperature zone the V content in MC carbide gradually increases and the change of Nb content is very small with temperature drop, while less than 900℃ MC changes constitutionally into VC. This rule is in agreement with experimental study[7]. Also can see, the Nb content in MC of calculational steel containing 0.25Nb carbide is higher than that of calculational steel containing 0.15Nb at each temperature, and V content in MC carbide also reduced correspondingly, as well as the ratio of MC carbide in the steel is increasing.

The phase type and mole fraction of the carbides in calculational steel at three temperature were listed in Table 3. Among them, the annealing carbide of calculational steels is estimated by calculating carbide at 650℃, and the quenching carbide is estimated by calculating carbide at 1150℃, and the tempering carbide is analysed by that at 520℃. Calculated and experimented results show that[3], the carbide type and quantity of annealing carbide and quenching carbide basically are in agreement with the computational values. The carbide type and number of

tempering carbide of calculated values are different with experimented results, Nevertheless, the tempering carbide can be analyzed by equilibrium carbide phase at tempering temperature and the effect on secondary hardening is estimated in turn. By the ratio of a kind of carbides at 520℃ can see, the ratio of MC carbide and M_6C carbide increases with the increasing of Nb content in the steel, so the tempering temperature of highest hardness is corresponding to about 530℃～540℃[3].

TABLE 3 TEPE AND RATIO OF EQUILIBRIUM CARBIDE PHASE OF THE CALCULATIONAL STEELS

Nb /wt%	Carbide at 650℃	Carbide at 1150℃	Carbide at 520℃	
	Type-ratio/mole%	Type-ratio/mole%	Type-ratio/mole%	Rise/mole%
0	1.27MC-7.57$M_{23}C_6$-5.11M_6C	2.13M_6C	1.24MC-7.92$M_{23}C_6$-4.72M_6C	11.75
0.15	1.45MC-7.12$M_{23}C_6$-5.15M_6C	0.63MC-1.52M_6C	1.39MC-7.53$M_{23}C_6$-4.80M_6C	11.57
0.25	1.56MC-6.83$M_{23}C_6$-5.19M_6C	0.87MC-1.34M_6C	1.48MC-7.27$M_{23}C_6$-4.84M_6C	11.38

4 Hardness calculation and heat treatment temperature

By hardness calculation method of quenching and tempering of Yongqing Ma[2], first it is to calculate the austenite matrix composition in the quenching temperature. Table 4 lists the austenite matrix composition and mole fraction of undissolved carbide of the calculational steels at three quenching temperature respectively. The undissolved carbide type and mole fraction is a measure whether the austenite grain coarsening and wear resistant [3].

TABLE 4 QUENCHING MATRIX COMPOSITION AND CARBIDE FRACTION OF CALCULATIONAL STEEL

Nb /wt%	Quench	Quenching matrix composition/ *wt*%									Carbide
	T/℃	C	Si	Mn	Cr	W	Mo	V	Nb	Ni	type-ratio/%
0	1050	0.44	0.48	0.41	6.48	0.72	2.84	0.44		0.37	0.56MC; 5.00M_6C
	1100	0.51	0.48	0.40	6.48	0.96	3.12	0.60		0.36	0.20MC; 3.81M_6C
	1150	0.57	0.48	0.39	6.45	1.29	3.78	0.73		0.36	2.13M_6C
0.15	1050	0.41	0.48	0.41	6.50	0.77	2.64	0.38	0.0024	0.37	1.03MC; 4.49M_6C
	1100	0.46	0.48	0.40	6.49	1.03	3.25	0.49	0.0047	0.36	0.83MC; 3.14M_6C
	1150	0.52	0.48	0.39	6.46	1.39	3.90	0.60	0.0090	0.36	0.63MC; 1.52M_6C
0.25	1050	0.39	0.48	0.41	6.51	0.79	2.68	0.36	0.0032	0.37	1.24MC; 4.31M_6C
	1100	0.44	0.48	0.40	6.50	1.06	3.29	0.46	0.0059	0.36	1.05MC; 2.95M_6C
	1150	0.50	0.48	0.39	6.46	1.42	3.95	0.57	0.0169	0.36	0.87MC; 1.34M_6C

Basis of the austenitic composition at quenching temperature the quenching hardness value of the alloy steel can be calculated from[2]

$$Hc=\alpha(1+\beta)/(0.00915\alpha+0.00527), \quad (1)$$

here α is the square root of carbon content in the matrix and β is correction coefficient of solid solution strengthening, and

$$\beta=0.0079Si+0.0067Mn+0.0058Ni+0.0038Mo+0.0035V+0.0032W+0.0031Cr. \quad (2)$$

The balanced carbon formula of martensite matrix can be writed as

$$C_p=0.011W+0.02Mo+0.057Cr+0.19V, \quad (3)$$

here the coefficients are carbon contents of $(W,Fe)_6C$, $(Mo,Fe)_6C$, $(Cr,Fe)_{23}C_6$ and VC carbides respectively, and alloy elements are from the matrix composition. The saturation level of carbon *Cs* in the matrix is C_s/C_p, and the tempering hardness value can be obtained from

$$H_S=a(1+b)/(0.0127a+0.00297), \quad (4)$$

in which *a* is the square root of the saturation level of carbon in the matrix, and carbide precipitation correction factor *b* is as

$$b=0.00374(Cr-6.6877)+0.00907(W-2.7554)+0.01521(Mo-1.3777)+0.04194(V+Nb-0.5961). \quad (5)$$

The hardness calculation of quenching and tempering of the calculational steels at different temperatures was listed

in Table 5, which also gives the calculation factor and correction coefficient for a reader's confirmation. Can be seen from table 5, while the quenching temperature is higher than 1100℃, the hardness calculation of quenching and tempering of the steels is all higher. When the quenching temperature of 1150℃ the highest tempering hardness is HRC64-65, and highest hardness decreases slightly with the Nb content increasing of the steel as slightly lower C content and alloy contents in austenite matrix at the same quenching temprature (see Table 4 and 5).

TABLE 5 HARDNESS CALCULATION OF THE CALCULATIONAL STEELS AT DIFFERENT TEMPERATURE

Nb	Quenching hardness calculation				Tempering hardness calculation					D-value of
/wt%	T/℃	α	1+β	/HRC	Cp	a	1+b	T/℃	/HRC	hardness
0	1050	0.6636	1.0435	61.05	0.5189	0.9213	0.9968	520	62.60	1.10
	1100	0.7126	1.0457	63.20	0.5568	0.9550	1.0097	530	63.87	0.67
	1150	0.7544	1.0495	65.04	0.5969	0.9764	1.0281	540	65.31	0.27
0.15	1050	0.6366	1.0427	59.83	0.5043	0.8965	0.9922	520	61.96	2.13
	1100	0.6800	1.0461	61.90	0.5400	0.9254	1.0078	530	63.35	1.45
	1150	0.7230	1.0499	63.87	0.5774	0.9515	1.0257	540	64.83	0.96
0.25	1050	0.6235	1.0428	59.24	0.5024	0.8796	0.9916	520	61.68	2.44
	1100	0.6667	1.0463	61.35	0.5368	0.9100	1.0077	530	63.12	1.77
	1150	0.7099	1.0501	63.36	0.5741	0.9368	1.0257	540	64.63	1.27

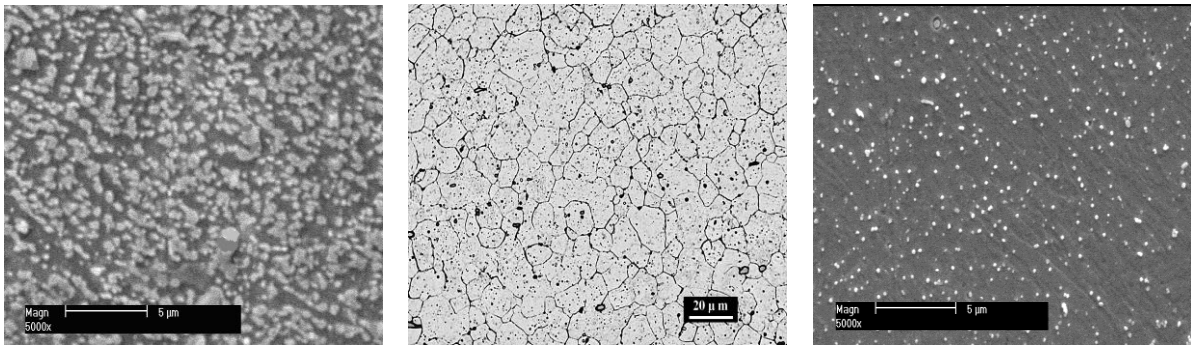
5 Experimental steel and its application

According to alloy design calculation, α↔γ transition temperature of calculational steel is A_1=835℃, so the annealing temperature of the steel is 850℃~860℃. The quenching temperature is 1100℃~1150℃ which can obtain higher quenching hardness, and the undissolved carbide mole fraction is >2% which can effectively prevent the excessive growth of austenite grain. The tempering temperature of the steel is 530℃~540℃ according to analysis of the types and amount of different carbides during tempering precipitation, and the tempering hardness can reach HRC63-65[4]. The experimental steel melted by alloy design composition range (see Table 1) has been used for manufacturing machinery knives by brazing-jointing edge steel.

TABLE 6 HARDNESS AND MICROSTRUCTURE OF HEAT TREATMENT OF THE EXPERIMENTAL STEEL

Annealing		Quenching with brazing			Tempering		
T/℃	HB	T/℃	Grain size/μm	HRC	T/℃	Carbide size/μm	HRC
850	245～255	1150	≈13.5	62～-63.5	540	＜1.5	63.5～65.2

Heat treatment hardness and microstructure feature of this edge steel of machinery knives are listed Table 6. Fig.4(a), (b) and (c) show the microstructures of heat treatment of experimental edge steel after annealing, quenching and tempering respectively. The results show that the distribution of the fine annealing carbide is uniform, the quenching grain size is about 13.5μm, and the volume fraction of undissolved carbide is larger than 3% and the average size of undissolved carbide is <1.5μm among major fine carbide size of 0.2μ～0.5μm. The tempering hardness of edge steel is HRC63.5-65.2, which basically is consistent with the alloy design calculation.



(a) Annealing (b) Quenching (c) Tempering

FIG.4 MICROSTRUCTURE OF THE EXPERIMENTAL STEEL

There is a large number of tiny undissolved carbides MC in tempering microstructure of the edge steel adding Nb. This reason has two aspects: first, adding a little Nb can control the refinement of MC carbide size evidently owing to the greater dissimilarity in electronic structure and atomic size between Nb and Fe than between V and Fe[6,8]; next, as the Mo ratio of MC carbide in the steel containing high Mo content is higher too, so the higher Mo will promote the nucleation of MC carbide dispersedly[9]. These fine carbides with high hardness have an important role for raising the edge sharpness and wear resistance of machinery knives. At present, the steel has been used for manufacturing machinery knives including the slicer cutting knife for wood working and the shearing knife for paper products industry.

6 Concluding remarks

There are four aspects on alloy design of Cr-W-Mo-V alloy steel, which is of the alloy composition design calculation, the phase constitution and microstructure design prediction, the process technology design and the forecast of property or performance. Machinery knives are thin edge blade for cutting non-metallic materials. They must have superior performance, which not only have the high hardness, high toughness, high wear resistance and nicer heat resistance, but also have the higher resistance to fatigue fracture and the higher resistance to carbide spalling from knife edge. Especially, the using performance of machinery knives for wood working has higher level comparing with other tool, which is a characteristic of thin blade tool. Therefore, the high quality edge steel of machinery knives all is using special tool steel of manufacturing industry. Copper brazing is one of the edge steel joining method of machinery knives. This designed high alloy steel has not only excellent properties of edge steel of machinery knives but also to adapt to copper brazing and quenching at the same time. Consequently, the alloy design of the steel is content with many technical index and conditions, so alloy design must carry out large amount of calculation and comparison too. The present results again show that the alloy design calculation of Cr-W-Mo-V tool steel is in agreement with the experimental results using above-method. The practice of alloy design calculation and experimental steel shows that the expectant objective can be obtained by theoretic design adding a small quantity of technical tests.

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