DEVELOPMENT OF NIOBIUM BEARING ALLOYS IN THE PEOPLES REPUBLIC OF CHINA

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Abstract

The paper presents a brief review of the use of niobium-bearing alloys in China including HSLA steels, constructional steels, high-speed steels, stainless steels and corrosion-resistant alloys, heat-resistant steels, high-temperature alloys, precision alloys, etc.

Niobium was discovered by the British chemist C. Hatchett in 1801. He named it columbium (Cb) in honor of the North American source of the ore sample he studied. In 1844, the German chemist, H. Rose discovered two different elements during analyzing Columbite ores, one of which was tantulum, and named the other one Niobium (Nb), after Tantalus' daughter Niobe in Greek mythologies. In 1866 C. Marignac proved that Nb and Cb were the same element. Therefore, in the periodic table the symbol of the 41st element is either Nb or Cb.

The application of niobium in steel began in the thirties of this era. In 1940, a U.S. patent was granted to F. M. Becket, et al. In fact, people did not use niobium steel until C-Mn-Nb steel plates were produced in United States in 1958 (1).

The application of niobium in China began in low carbon Mn-Nb steels also. In the beginning of the sixties we researched and developed a group of low carbon niobium-bearing killed or semi-killed steels. In the beginning of the seventies normalized or quenched and tempered HSLA steels containing both molybdenum and niobium were developed, and at the same time, niobium was used in tool steel, heat resistant steel or alloy, stainless steel or corrosion resistant alloy and precision alloys, etc. The general condition of research and development of niobium-bearing alloys in these areas is as follows.

The Application of Niobium in HSLA Steel

At the end of the fifties, HSLA steel was still a new group of steels. In the middle of the sixties Bau-Tou and Tienjing steel plants developed a set of as-rolled niobium-bearing manganese steels, such as 09MnNb, 14MnNb, 16MnNb, etc. The yield strength of these steels was 290 to 340 MPa. The niobium content of which was between 0.015 percent to 0.05 percent. Bao-Tou steel company produced semi-killed 10MnNb and 14MnNb by utilizing residual niobium in the iron. These two kinds of steels are widely used in structural shapes and small diameter pipe and chemical pressure vessels, etc.

Later, to increase strength and toughness, the 18MnMoNb steel was used. The mechanical properties of this steel at room temperature and up to 450 C were good. It has been used in different types of pressure vessels. A typical one is a tower for synthetic urea, the cylinder of which was build by welding plate of 115 mm thickness.

To prevent cracking during stress-relief annealing of this steel after welding, the weldment must be isothermally heat treated at 180 C in place of stress-relief anneal (2).

Several years ago, a high yield strength 6 690 MPa) 14MnMoNbB was produced and used to build high pressure water pipe for a water power station (3). The toughness of this steel at low temperature is shown in Figure 1.

In addition, the following niobium-bearing steels have also been developed:

1. Cryogenic steel 06Al NbCuN - The formability and weldability of this steel are good. It has been used in oil refineries and synthetic rubber industries and was successful (4). Comparison of fracture toughness between this steel and 3.5 percent Nickel steel is shown in Figure 2.

2. Sea water corrosion resistant steel 10MoPNbRE which was used for wharf facilities.

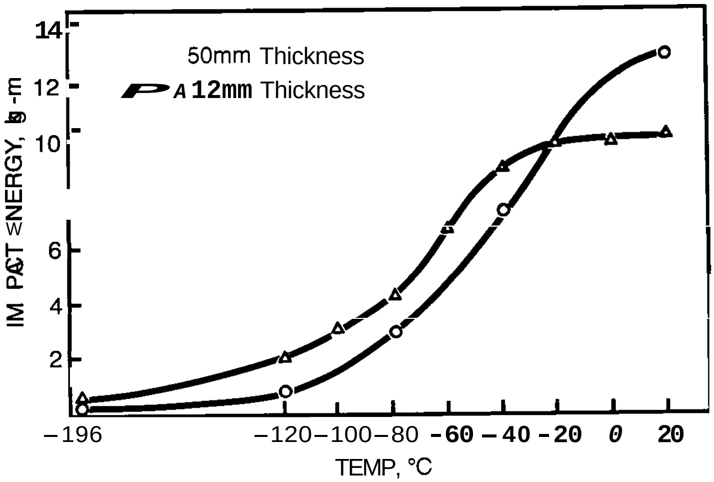

Figure 1. Toughness of 14MnMoNbB at different temperatures.

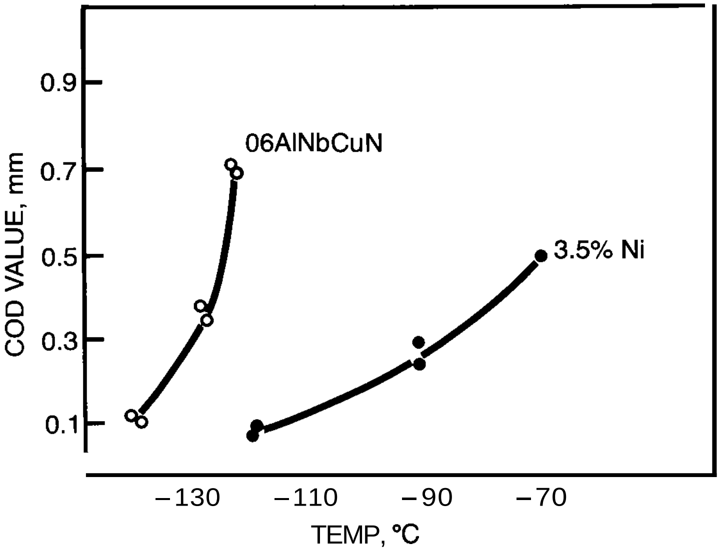

Figure 2 Comparison of COD value between 06AlNbCuN and 3.5% Ni steel.

3. 10MoWVNb steel used for hydrogenation equipment. The creep rupture strength of this steel is shown in Table I (5).

Table II summarized the classification, trade designations and compositions of principal types of niobium-bearing HSLA steels.

Meanwhile, investigation of the effect of control rolled process on the recrystallization characteristics or the relationship between microstructure and mechanical properties has been done on some steels listed in Table II e.g. 09MnNb.

Table I. The extrapoloted creep rupture strength of 10 MoWVNb steel.

Temp. (°C)	σ10000 (MPa)	σ100000 (MPa)
500	225	176
530	147	120
600	106	72
620	67	53

Application of Niobium in Structural Alloy Steels

There are a few niobium-bearing steels in structural alloy steels. Two niobium-bearing alloy structural steels, 40MnNbRE and 40MnMoNb have been developed only. The latter steel (0.4% C - 1.10% Mn - 0.60% Mo - 0.09% Nb) was strengthened by both molybdenum and niobium. Niobium has a pronounced effect on the yield strength of these steels. This effect is more evident when it is used together with molybdenum (6).

Application of Niobium in Tool Steels

High speed steel

Several new high speed steels have been developed in China. The common feature of these steels is cobalt-free and contains Nb, Al and Si, etc. (7). The approximate compositions of these steels are summarized in Table III.

Table III. Approximate composition of several niobium-bearing high speed steels.

Trade designation	C	Mn	W	Mo	Cr	V	Nb	Al	Si
B201	1.60	≤0.04	6.0	5.5	4.1	4.7	0.35	0.5	1.2
B212	1.53	≤0.04	18.0	-	4.1	3.4	0.15	1.3	1.2
B223	1.73	≤0.04	4.0	7.1	4.1	4.1	0.40	1.2	1.0

Niobium-bearing high speed steel has higher red hardness and wearability. The optimum content of niobium is 0.8-1.0 percent. The relationship between hardness and tempering temperature of niobium-bearing high speed steel mentioned above is shown in Figure 3. These steels have been successfully used in making drill head and drawknife, etc.

Table 11. Compositions of principal types of Nb-bearing HSLA steels.

Trade Designation	Condition	Chemical Composition (wt%) C	Si	Mn	P	S	Ni	Mo	Nb	Cu	other
09 Mn Nb	R/CR	≤ 0.12	0.2/0.6	0.8/1.2	≤ 0.05	≤ 0.05			0.015/0.05		
14 Mn Nb	R	0.12/0.18	0.2/0.6	0.8/1.2	≤ 0.05	≤ 0.05			0.015/0.05		
16 Mn Nb	R	0.12/0.20	0.2/0.6	1.2/1.6	≤ 0.05	≤ 0.05			0.015/0.05		
18 Nbb	R	0.22	≤ 0.17	0.65	≤ 0.05	≤ 0.05			0.015/0.05	≤ 0.35	
14 Mn Nbb	R	0.12/0.18	≤ 0.17	1.2	≤ 0.05	≤ 0.05			0.015/0.05	≤ 0.35	
18 Mn Mo Nb	N+T	0.23	0.37	1.65	≤ 0.04	≤ 0.045			0.025/0.05		
14 Mn Mo NbB	Q+T	0.12/0.18	0.15/0.35	1.3/1.8	≤ 0.03	≤ 0.03		0.45/0.7	0.02/0.06	0.2/0.4	B 0.005/0.003
13 Mn Ni Mo Nb	N+T	≤ 0.16	0.15/0.5	1.0/1.6	≤ 0.025	≤ 0.025	0.6/1.2	0.2/0.4	0.1/0.03		Cr 0.2/0.4
06 Mn Nb	R/N	≤ 0.07	0.17/0.37	1.2/1.6	≤ 0.03	≤ 0.03			0.02/0.04		
06 Al Nb Cu N	Q+N	≤ 0.08	≤ 0.35	0.9/1.3	≤ 0.02	≤ 0.035			0.04/0.09	0.3/0.5	N 0.01/0.018
10 Mo W V Nb	N+T	0.07/0.13	0.05/0.8	0.5/0.8	≤ 0.04	≤ 0.03			0.06/0.12		V 0.3/0.5
12 Si Mo V Nb	R	0.08/0.14	0.05/0.8	0.6/0.9	≤ 0.04	≤ 0.03			0.04/0.08		V 0.3/0.5

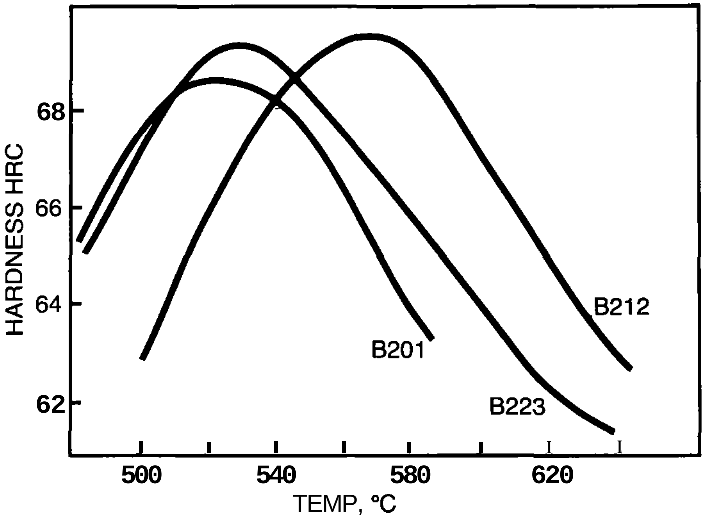

Figure 3. The hardness of niobium-bearing high speed steels.

Die steels

There are two niobium-bearing die steels - 4Cr3W - 4Mo2VTiNb and 65Cr-4W3Mo2VNb steels. The former belongs to hot working die steel and has been used for precision forging and high speed forging dies working at temperature below *900* C. The quenched hardness, thermal fatigue strength and resistance to tempering of the steel is rather high. The latter is a high toughness coldworking die steel. The addition of niobium can increase the normal rupture strength of Cr-W-Mo-V steel *(8)*. Niobium delayed the dissolution of carbides so that in the matrix existed more lath martensite and hence the toughness of the steel was improved. The results in practice showed that this cold working die steel possesses higher bending and twisting strength and higher multi-impact strength.

Use of Niobium in Stainless Steels and Corrosion Resistant Alloys

Niobium has been added to ferritic, austenitic and martensitic stainless steels. The results of industrial application showed that the presence of 0.4-0.6 percent niobium in ferritic stainless steel 0Cr13Si4NbRE will increase toughness and resistance to oxidizing medium of this steel. It has been used for making valves and pump-body facilities for concentrated nitric acid. There are three different Nb-bearing stainless steels i.e. 0Cr17Ni4Cu-3Nb, 1Cr18Ni11Nb and Cr18Ni20Cu2Nb steels (austenitic type or precipitation hardening type).

The 0Cr17Ni4Cu3Nb steel possesses high strength after solution treatment and has been used for machine parts which require high strength and high wearability, such as rotating drum or spring of contrifugal machine (9). The experimental results showed that resistance of this steel to many corrosive media is similar to that of 18-8 type austenitic stainless steel (Table IV).

Table IV. The corrosion rate of 0Cr17Ni4Cu3Nb steel in various media.

Condition		8 hr in boiled 5% H_2SO_4	48 hr in 10% H_2SO_4 at ambient temp.	8 hr in in boiled 40% HNO_3	48 hr in 30 C 10% HCl	8 hr in boiled 8% CH COOH
Corrosion Rate (g/m^2 h)	annealed	178	4.58	0.25	0.51	0.83
		178	4.69	0.28	0.50	0.79
	aged	431	6.30	0.31	0.50	0.10
		427	6.27	0.27	0.49	0.15

The resistance of 1Cr18Ni11Nb steel to intergranular corrosion was good. It has been used in sea water, alkaline medium and many acids and can be polished. The approximate composition of which is as follows: C 0.10 percent, Si 1.0 percent, Mn 2.0 percent, Cr 20 percent, Ni 12 percent, Nb 8 x C ÷ 1.5 percent, S 0.030 percent, P 0.035 percent. After heated at 1100 ~ 1150 C and quenched in water, the mechanical properties of this steel are tensile strength 540 MPa, yield strength 200 MPa and elongation(s) 40 percent. It has been widely used in industries of food, sugar making, wine brewing, fermentation and condensed milk, etc., and can be used as core material of welding electrode for welding nickel chromium steels also (10).

Because Cr18Ni20Mo2Cu2Nb stainless steel contains niobium about 12 x carbon percent, it possesses considerably higher resistance to intergranular corrosion than titanium-bearing stainless steel. After heating at 1050 ~ 1100 C and quenched in water, this kind of steel had a tensile strength of ≥ 539 MPa, an elongation of ≥ 40 percent and a reduction of area) 35 percent. This kind of steel is used chiefly for facilities which require resistance to strong corrosive media and may be used as the core material of welding electrode for welding high nickel-chromium-molybdenum steels (11).

Recently a niobium-bearing Cr-Ni-Mo maraging stainless steel was developed. The steel had a good combination of certain tensile strength and high toughness (12). It was used for large section machine parts such as wheel of carbon dioxide centrifugal compressor in chemical industries. This niobium-bearing alloy contains approximately 0.02 percent C, 0.05 percent Mn, 0.004 percent S, 0.01 percent P, 0.2 percent Si, 8 percent Ni, 15 percent Ct, 1.5 percent Mo and 0.4 percent Nb. Its mechanical properties at room temperature and 400- 550 C are shown in Table V and Table VI.

Niobium-bearing 17-4 PH casting alloys not only have been widely used in airplanes, but in petroleum, chemical, ship building industries and nuclear power plants also. The average mechanical properties of this alloy are as follows: yield strength> 1030 MPa, tensile strength> 1220 MPa, elongation ≥ 6 percent, reduction of area ≥ 15 percent, hardness ≥ 40 HRC. Shanghai Iron and Steel Research Institute has investigated the process technology, heat treatment regime and the relationship between microstructure and mechanical properties, etc. of this steel (13).

00Cr 25Ni 25Si 2V 2Nb (SCR-3) steel developed at the beginning of the seventies is a new type of steel which possesses rather high strength and rather good resistance to intercrystalline corrosion and has been used in concentrated chloride or in chloride-containing solutions at high temperature and high pressure. However, this steel became brittle when it was used in the temperature range of 600-900 C. In order to prevent this kind of brittleness the effect of nickel content has been investigated (14). The result showed that after heat treating at 600-900 C, the impact toughness of the alloy containing lower nickel is considerably lower than that of the alloy containing higher nickel (≥ 35%). It is due to the fact that the former alloy after being heated at 600-900 C precipitated a vast amount of σ phase, the maximum of which was about 10 percent, but on the contrary the latter alloy precipitated less than 3 percent.

Table V. The mechanical properties of maraging stainless steel.

Specimen	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)	Reduction of area (%)	Impact energy (kg-m)
φ 19 mm plate L direction	853	911	22.5	78.5	> 32.5
20 mm plate L direction	809	867	22.5	71.5	> 32.0
150 mm forging L direction	858	887	21.0	69.5	29.4

Table VI. Elevated temperature mechanical properties of 150 mm forging.

Temp. (°C)	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)	Reduction of area (%)
400	676	689	14.0	77.0
450	642	676	17.0	79.0
500	603	603	16.5	80.5
550	495	505	21.5	80.5

The Application of Niobium in Heat Resistant Steels and High Temperature Alloys

At the beginning of the seventies, in order to develop better material for use in steam or gas turbine blades, strong carbide-forming elements Nb, V or Mo were added to the 12Cr type of martensitic stainless steels, e.g. 1Cr 11Co 6MoVNbBN (Nb ≤ 0.45%) steel has been used for turbine disks and turbine blades of jet engines (15).

Three more heat resistant steels have been developed. 1Cr14Ni18W2Nb BRE steel (0.9-1.5%Nb) has been used for turbine blades of gas turbines working at ≤ 680 C. 3Cr19Ni9MoWNbTi steel has been used for turbine blades, plates rotors, etc. working at 600 C for a long period. After water quenching from 1150-1180 C and soaking at 750 C for 12-15 hours, mechanical properties achieved are shown in Table VII (16).

Table VII. The mechanical properties of 3Cr19Ni9MmoWNbTi steel.

	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)	Reduction of area (%)	Impact energy (kg-m)
L direction	323-451	735-823	31- 49	40- 49	9.5
C direction	343-568	598-843	9 - 29	10- 42	2.8 ~ 8.0

The approximate composition of this steel was 0.28-0.35 percent C, 18-20 percent Cr, 8-10 percent Ni, 1.0-1.5 percent Mo, 1.0-1.5 percent W, 0.2-0.5 percent Nb. It is worth mentioning a third niobium-bearing heat resistant steel 7 Mn20A15MoVNb (0.15-0.30%Nb) which contains neither chromium nor nickel. After heated at 1060 C water quenched and aged at 750 C, the ultimate tensile strength of this steel at room temperature was above 735 MPa. It has been used for the inlet or outlet valves working at temperature below 500 C in large power locomotive and marine diesel engines.

Meanwhile, the effect of niobium on the mechanical properties of 3Cr-20Ni10Mn 9MoNbBN steel (so-called LF steel) used for some high duty diesel engines has been investigated. Experimental result showed that 0.3-0.5 percent niobium will improve high temperature fatigue strength, creep strength, resistance to corrosion, and resistance to corrosive exhaust products.

Nickel-base alloy GH33 was used for turbine disks of jet engines, its working temperature being 700 C. After addition of 1.5 percent niobium to this alloy, it became age-hardening nickel-base high temperature alloy (trade designation GH33A). The mechanical properties were considerably improved. The chemical composition and the effect of niobium on the mechanical properties of GH33 and GH33A were shown in Table VIII, IX and X (17).

Table VIII. The approximate chemical composition of GH33 and GH33A.

Alloy	Nb	C	Cr	Al	Ti	B	Ce	Ti + Al	Ti/Al
GH33	-	0.044	20.0	0.92	2.84	0.01	0.01	3.76	3.09
GH33A	1.53	0.044	19.9	0.96	2.92	0.0078	0.01	3.88	3.03

Table IX. The effect of Niobium on the mechanical properties of GH33 alloy.

Room Temperature

Alloy	Yield strength (MPa)	Tensile strength (MPa)	Elongation %	Reduction of area %	Impact energy kg-m	HB
GH33	743	1060	15.0	15.4	3.4	303
GH33A	815	1215	30.9	34.8	6.9	329

700 C

Tensile strength (MPa)	Elongation %	Reduction %
940	17.6	19.5
982	18.9	19.0

Table X. The effect of niobium on creep properties.

Alloy	Total elongation %	Residual elongation %	Elastic elongation %	Creep rate $hour^{-1}$
GH33	1.0316	0.9628	0.2884	10×10^{-5}
GH33A	0.4672	0.2164	0.2818	1.9×10^{-5}

Niobium-bearing high temperature alloy GH14 was used for combustion chambers. It has the features of lower nickel content, higher high temperature strength, etc. (18). The composition of the alloy is as follows: C 0.08 percent, Mn 1.50 percent, Si 0.60 percent, P 0.020 percent, S 0.015 percent, Cr 19-22 percent, Ni 28-34 percent, W 7.5-9.5 percent, Mo 5-2.5 percent, Nb 0.8-1.3 percent, N 15-0.25 percent, B 0.01, Ce 0.05. After aging at 550-700 C for 100-200 hours, the mechanical properties of this alloy basically did not change. After aging at 800-900 C for 100-200 hours due to the precipitation of M_6C and Laves phase the strength at room temperature was markedly improved, but the high temperature strength changed very little, and the plasticity at room temperature decreased. After aging at 950 C for 100-200 hours, the strength at room temperature and high temperature was approximately the same as the as-received condition but the plasticity at room temperature was lower than that of the as-received condition. However, in all the above conditions the lowest value of reduction of area was above 20 percent.

GH169 alloy contained about 5.5 percent niobium (19). After heat treatment, a large amount of precipitation hardening phasey" (Ni_3Nb) was formed. After cold rolling and 900 C solution treatment, the hardness of this alloy was the same as that in the cold rolled condition (HV400). However, after solution treatment at a temperature higher than 950 C, the hardness decreased abruptly because of recrystallization.

Use of Niobium in Precision Alloy

One of the widely used magnetic materials in the Chinese electronic industries is 80 percent Ni - 8 percent Nb - 12 percent Fe alloy which possesses good initial permeability pa and maximum permeability μm. At the same time, after tempering at high temperature, it still maintains rather high hardness. The physical properties of this alloy are shown in Table XI and Table XII (20).

Table XI. The chemical composition and physical properties of Ni-Fe-Nb alloy.

Alloy	Chemical Composition (wt%) Ni	Nb	C	S	Fe	Curie point To (°C)	Saturated Induction (GS)	Elastic modulus E(dyne/cm^2)	Lattice constant (Å)
Ni-Fe-Nb	79.38	7.82	.003	.002	the rest	297	6000	2.156×10^{12}	3.5711

Density (g/cm^3)	Linear expansion coefficient
8.8	12.48×10^{-6}

Table XII. The magnetic properties of Ni-Fe-Nb alloy after different heat treatments.

Heat Treatment	Initial permeability μ 0.001 (Gs/Oe)	Maximum permeability μm (Gs/Oe)	Coercive force Hc (Oe)	Saturated induction Bs (Gs)
1150 C, 2h Furnace cooled to 300 C	80000	400000	0.05	6000
1150 C, 2 h Furnace cooled to 300 C; aged at 780 C, 6h, Furnace cooled	17000	85000	0.24	6000

When aluminum or/and molybdenum is added to the Ni-Fe-Nb alloy, the modified alloy can be rolled to 0.02-0.2mm thickness strip after softening treatment. The microstructure is a typically modulated structure which has been proved by X-Ray analysis, TEM observation and hardness measurement (21). The precipitation of γ' phase Ni_3 (Al, Nb) will increase the hardness and decrease the sensitivity to stress of this kind of alloy. The static and dynamic soft magnetic properties, the workability and wearability of this alloy are good. It is a good material for various kinds of magnetic heads,

The typical Ni-Fe-Nb alloys containing aluminum or/and molybdenum were Ni-Fe-Nb-Mo-Al and Ni-Fe-Nb-Al alloys. The chemical compositions, physical properties and the optimum magnetic properties are shown in Table XIII and Table XIV respectively. Having the best combination of various properties these two alloys were widely used materials for magnetic heads of digital type machines and special recorders (22).

Table XIII. The chemical composition and physical properties of typical alloys for magnetic heads.

Alloy	Chemical Composition (wt%)					Saturated induction Bs, (Gs)	Curie point To, (C)	Density (g/cm³)	Resistivity ρ, (μΩ-Cm)	Hardness (HV)
	Ni	Nb	Al	Mo	Fe					
Ni-Fe-Nb-Mo-Al	78.98	7.13	0.46	2.07	the rest	4900	300	8.77	88	290
Ni-Fe-Nb Al	79.66	8.09	1.14	-	the rest	4800	297	8.66	85	350

Table XIV. The optimum magnetic properties of typical alloys for magnetic heads.

Alloy	Initial permeability μ 0.001 (Gs/Oe)	Maximum permeability μm(Gs/Oe)	Coercive force Hc, (Oe)	Residual induction Br, (Gs)	Saturated induction Bs, (Gs)	Heat Treatment
Ni-Fe-Nb-Mo-Al	80000	330000	0.05	2400	4800	1100-1150 C x 3 h in vacuum, Furnace cooled
Ni-Fe-Nb-Al	15000	150000	0.013	3700	4800	1000-1200 C x 2h in vacuum, Furnace cooled 970 C x 1 h in Hydrogen atm. fast cooling.

The parts which are sensitive to elasticity of the instruments used in or near the magnetic field must be nonmagnetic. The rate of magnetization of niobium base alloy is about 10^{-6}. These alloys are the optimum materials of constant elasticity used at high temperature. For instance, Nb-40Ti5.5Al alloy can be used in the temperature range of -60- 400 C for a long time. After improving the resistance to oxidation, this alloy can be used at temperatures up to 1000 C (23). The approximate composition is 40 percent Ti, 0.06 percent C, 5 percent aluminum and niobium being the rest. Because of its low elastic modulus and high elastic limit, the ratio of stored energy σ^2/E increases, which improves the sensitivity of the instrument significantly. The effect of heat treatment temperature on the hardness of this alloy is shown in Table XV.

The alloy can be aged hardened either in the cold rolled or water quenched condition. After age-hardening, the elastic modulus of the alloy is about 98×10^3 - 113×10^3 MPa which is nearly the same as the original condition, but the tensile strength and the elastic limit can be considerably increased (the elastic limit will be 980 MPa).

Table XV. The effect of heat treatment on the hardness of Nb-40Ti-5.5Al alloy.

	Heat Treatment Temperature (°C)										
Condition	R.T.	300	400	500	550	600	650	700	800	900	1000
Cold rolled 70%	329	334	340	360	387	419	380	345	289	252	244
1000 C x lh W.Q.	238	242	244			247	255	268	252		

The Application of Niobium in Other Ferrous Materials

Besides the different types of alloys mentioned above, niobium has also been used in other ferrous materials in China (24).

Niobium-bearing cast steel rolls

About 50 Nb-bearing (0.04-0.06%Nb) cast steel rolls have been tried. The surface hardness at high temperature of niobium-bearing cast steel rolls in comparison with niobium-bearing or molybdenum-bearing cast steel roll is shown in Table XVI. The function of niobium in this kind of product was to decrease the amount of pearlite and to spheroidize the graphite and make it finely divided.

The working temperature of this kind of roll was rather high and its fatigue strength at high temperature was good so that premature fracture was avoided.

Table XVI. The comparison of Niobium-, Nickel-, and Molybdenum-bearing cast steel roll.

Type of roll	Hardness of R.T. (HV)	Decrease of hardness (-ΔHV) at high temperature (20 kg load), (°C) 400	500	600
Nb-bearing	545	24	55	72
Ni-bearing	540	28	58	73.5
Mo-bearing	545	47	61	75.0

Niobium-bearing cast iron cylinders for automobiles

The addition of about 0.3 percent niobium to the iron used for casting cylinders and rare earth treatment metal will significantly decrease the rate of corrosion of the cylinder.

Conclusion

Research and development of niobium-bearing alloys in China is still rather limited. However, we can predict that as part of the moderization of Chinese industries, research and development of niobium-bearing micro-alloyed steels and other niobium-bearing steels and alloys will be greatly intensified and the production of niobium-bearing alloys in China will increase significantly.

References

1. Science Promotion Society of Japan, Iron-making No. 19 committee, Iron, Steel, and Alloy Elements, Tokyo, 1966, Vol. 1, p. 723.

2. Wanp, Yingshu et al, Symposium of CISRI, 1979.

3. Zhang, Hongtao et al, Internal Research Report, CISRI, 1978.

4. Xue, Kaishi, Shanghai Metallurgy, 1980, No. 3, p. 45.

5. Zhang, Jianzhong, ibid, p. 27.

6. Ma, Yanji, Internal Research Report, CISRI, 1978.

7. Benggang, Tegang, 1979.

8. Huazhong Idustrial University, Effects of Nb in High Toughness Cold Die Steels, 1979.

9. Handbook of Mechanical Engineering, Mechanical Industry Publishing House, 1978, Materials Part, p. 12–28.

10. CISRI et al, Handbook of Alloy Steels, China Industry Publishing House, 1964, Beijing, V. 2, p. 111–346.

11. Ibid, III-355.

12. Wang, Haichun et al, Shang Steel Research, 1979, No. 2, p. 15.

13. Zhao, Guoqing et al, ibid, No. 3, p. 24.

14. Zhu, Erjin, Symposium of CISRI, 1979, p. 183.

15. Fu, Junyan, Internal Research Report, CISRI, 1980.

16. CISRI et al, Handbook of Alloy Steels, China Industry Publishing House, 1964, Beijing, V.2, p. 111–393.

17. Ma, Fujun et al, Symposium of CISRI, 1979, p. 295.

18. Shanghai Steel Research Institute, Depart. No. 3, High Temperature Group No. 1, Shanghai Steel Research, 1977, No. 2, p. 1.

19. Li, Li et al, Symposium of CISRI, 1979, p. 316.

20. Wang, Junjian et al, ibid, p. 277.

21. Zu, Wenchong et al, Journal of Metals, China, 15, 1979, No. 2, p. 252.

22. Xu, Wenchong et al, ibid, No. 4, p. 482.

23. Huan, Tewui et al, Symposium of CISRI, 1979, p. 452.

24. Informations of Conference on Niobium Steels Research, 1979, China, Baotou.