Journal of University of Science and Technology Beijing
Volume 11, Number 1, February 2004, Page 62

Elevated-temperature properties of one long-life high-strength gun steel

Maoqiu Wang, Han Dong, and Qi Wang

Division of Structural Materials, Central Iron & Steel Research Institute, Beijing 100081, China

(Received 2003-03-08)

Abstract: The hardness, tensile strength and impact toughness of one quenched and tempered steel with nominal composition of Fe-0.25C-3.0Cr-3.0Mo-0.6Ni-0.1Nb (mass fraction) both at room temperature and at elevated temperatures were investigated in order to develop high-strength steel for long-life gun barrel use. It is found that the steel has lower decrease rate of tensile strength at elevated temperature in comparison with the commonly used G4335V high-strength gun steel, which contains higher Ni and lower Cr and Mo contents. The high elevated-temperature strength of the steel is attributed to the strong secondary hardening effect and high tempering softening resistance caused by the tempering precipitation of fine Mo-rich M_2C carbides in the α-Fe matrix. The experimental steel is not susceptible to secondary hardening embrittlement, meanwhile, its room-temperature impact energy is much higher than the normal requirement of impact toughness for high strength gun steels. Therefore, the steel is suitable for production of long-life high-strength gun barrels with the combination of superior elevated-temperature strength and good impact toughness.

Key words: secondary hardening steel; elevated-temperature strength; hot hardness; impact toughness

1 Introduction

The mechanical properties such as tensile strength and impact toughness both at room temperature and at elevated temperatures are essential for high-strength gun steels since gun barrel is subjected to cyclic high temperature and high pressure during repeated gun firings [1-3]. Most gun steels currently used are Cr-Ni-Mo-V series medium carbon steels in quenching and high-temperature tempering condition with high strength and good toughness [4]. However, it is necessary to improve the elevated-temperature strength to meet with the increasing requirement of firing life span of gun barrels. It is well known that some hot working die steels have excellent hot hardness and wear resistance because of their relatively high alloy contents such as chromium, molybdenum and vanadium, which may lead to strong secondary hardening effect by forming alloy carbides at high-temperature tempering [5-6]. Hence, it is desirable to improve elevated-temperature hardness and strength of high strength gun steels by increasing Cr and Mo contents from normal contents of no great than 2.5%Cr and 1.5%Mo to 3%Cr and 3%Mo (3Cr-3Mo hereafter) so that firing life span can be extended. The heat treatment and microstructure of the 3Cr-3Mo gun steel were studied in previous papers [7-8]. The aim of the present study is to investigate the elevated-temperature mechanical properties of the steel with emphasis on tensile strength, hardness and impact toughness.

2 Experimental procedures

2.1 Experimental materials

The experimental steel was melted in a 500 kg non-vacuum induction furnace and then electro-slag remelted. The composition of the steel is as follows: Fe - 0.28C - 0.20Mn - 0.13Si-2.99Cr-2.86Mo-0.72Ni-0.11Nb-0.006P-0.008S (mass fraction, %). The ingot was heated to 1180°C and then forged to bars with dimension of ϕ90 mm×3000 mm, followed by annealing at 700°C for 24 h, then cooling to room temperature in air furnace. The commercial G4335V steel with chemical composition of Fe-0.40C-0.40Mn-0.25Si-1.28Cr-0.37Mo-3.14Ni-0.20V-0.012P-0.001S (mass fraction, %) in quenched and 600°C tempered condition was also used for comparison in elevated-temperature tensile strength.

2.2 Heat treatment

The 3Cr-3Mo steel bars were reaustenitized at 1050°C for 60 min, and then quenched into water to room temperature. The austenitizing temperature was chosen at 1050°C in order to completely dissolve the primary carbides with Mo and/or Cr [7]. After quenching, the steel bars were immediately tempered at 640°C for 240 min, followed by water cooling. The

---

Corresponding author: Maoqiu Wang, **E-mail:** maoqiuwang@hotmail.com

3Cr-3Mo steel has strong secondary hardening effect when it is tempered at around 575°C. The final tempering temperature was chosen at 640°C in order to obtain high impact toughness as well as high tensile strength [8].

2.3 Elevated-temperature tests

The heat-treated 3Cr-3Mo steel bars were then machined along the traverse section orientation to produce tensile specimens (ϕ5 mm×65 mm), hardness specimens (ϕ15 mm×10 mm) and impact specimens (10 mm×10 mm×55 mm, Charpy V-notch) for both room-temperature test and elevated-temperature test. Hardness tests were carried out with an elevated-temperature Micro-Vickers tester in vacuum environment at room temperature and at elevated temperatures in the range of 100-600°C. Tensile tests were conducted at a strain rate of 10^{-2}s^{-1} using an AMSLER-50 material testing machine at room temperature and at elevated temperatures in the range of 100-600°C. Impact tests were conducted at room temperature, low temperatures, and elevated temperatures in the temperature range of −100-300°C by cooling or heating to the required temperature before impacting. Tensile specimens of G4335V steel in the same dimensions were also prepared and tested at elevated temperatures.

2.4 Microstructural examination

Thin film specimens of the 3Cr-3Mo steel for Transmission Electron Microscope (TEM) observation were cut from the heat-treated bars, ground to about 50 μm, and electro-polished in a perchloric acid-methanol solution at −40°C. TEM observation was carried out in the JEM-2000FX type TEM, operating at 160 kV using bright field imaging. The fraction of alloy elements in the carbides were determined by analyzing the extracted residues using X-ray diffraction. Fractographs of the impact surface were observed in the JSM-6400 type Scanning Electron Microscope (SEM).

3 Results and discussion

3.1 Tensile properties and hardness

Figure 1 (a) shows the variations of Ultimate Tensile Strength (UTS, σ_b), 0.2% offset Yield Strength (YS, $\sigma_{0.2}$) and hardness of the 3Cr-3Mo steel with test temperature in the range of 20-600°C. It is obvious that UTS and YS decrease with increase of test temperature, from 1150 MPa and 965 MPa at room temperature down to 660 MPa and 590 MPa at 600°C, respectively. This is because the dislocations are easier to move at higher temperatures, resulting in early plastic deformation, yield and fracture [6]. When the test temperature is above 300°C, the tensile strengths decrease more sharply. It is also found that UTS decreases a little more quickly than YS does, which leads to an increase in YS/UTS ratio from 0.839 at room temperature to 0.894 at 600°C, as shown in **table 1**. The hardness also decreases with increase of test temperature, similar to tensile strength. A sharper decrease in hardness is also observed when the test temperature is above 300°C. The following equations can be used to approximately describe the variations of hardness Hv and tensile strengths σ_b and $\sigma_{0.2}$ with test temperature:

$$\sigma_b = 1150 - 0.536 \times (T - 20) \quad (1)$$

$$\sigma_{0.2} = 965 - 0.429 \times (T - 20) \quad (2)$$

$$\text{Hv} = 380 - 0.082 \times (T - 20) \quad (3)$$

where the test temperature T is between 20-300°C, and when T is between 300-600°C, then

$$\sigma_b = 1000 - 1.133 \times (T - 300) \quad (4)$$

$$\sigma_{0.2} = 845 - 0.850 \times (T - 300) \quad (5)$$

$$\text{Hv} = 357 - 0.293 \times (T - 300) \quad (6)$$

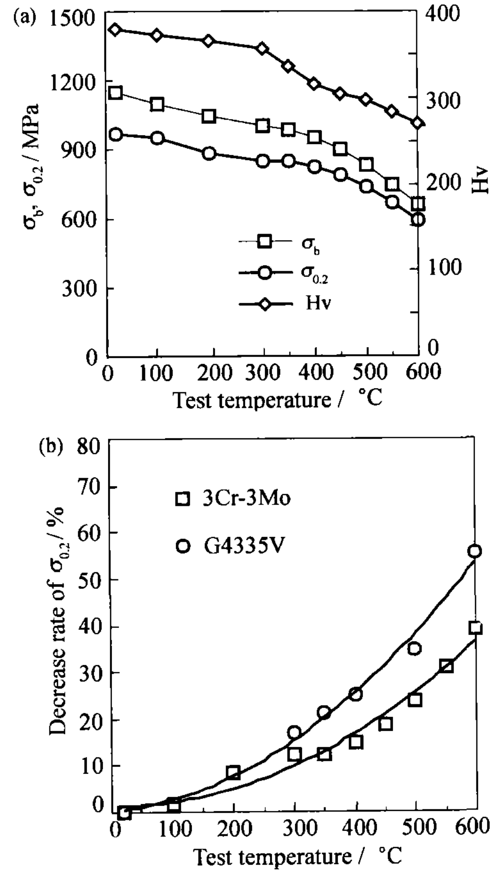

Figure 1 Tensile strengths and hardness (a) and the decrease rate of $\sigma_{0.2}$ (b) of the steels at various test temperatures.

From the above equations, it can be seen that the decrease rates of the strengths and hardness, which are represented by the corresponding slope against T, are more than doubled when the test temperature is increased to above 300°C. However, the strength do not change linearly with the test temperature, so another Decrease Rate (DR, in %) of Yield Strength (YS, in MPa) in comparison with Room Temperature Yield Strength (YS_RT, in MPa) is defined as expressed by equation (7). The calculated decrease rates of YS for the 3Cr-3Mo and G4335V steels at various elevated temperatures are shown in figure 1(b). It is found that the 3Cr-3Mo steel has much lower decrease rate than the G4335V steel, especially at higher test temperatures. For example, the decrease rate of G4335V steel at 350°C is about 21%, while that of 3Cr-3Mo steel is less than 13%. The higher the test temperature, the greater is the difference.

$$DR = [1 - YS / YS\_RT] \times 100\% \qquad (7)$$

Table 1 also gives the Tensile Elongation (TE) and Reduction of Area (RA) of the 3Cr-3Mo steel at various test temperatures, showing that increasing test temperature results in pronounced increases in TE and RA when the test temperature is above 450°C. However, no great changes of both TE and RA were found when the test temperature is in the range of 20-400°C, although the strength decreases obviously. Even the tensile specimens tested at room temperature appear to neck before fracture, giving rise to high RA values of more than 50%. A requirement of no less than 25% in room temperature RA is specified for high strength gun steels [4], and it is obvious that the 3Cr-3Mo steel has much higher ductility both at room temperature and at elevated temperatures than the requirement.

Table 1 Tensile properties of the 3Cr-3Mo steel at various test temperatures

Test Tempature/ °C	UTS / MPa	YS / MPa	YS/UTS	TE / %	RA / %	DR* / %
20	1150	965	0.839	13.5	57.0	0
100	1100	950	0.864	13.0	57.5	1.55
200	1050	885	0.843	13.5	56.5	8.29
300	1000	845	0.845	12.5	56.5	12.44
350	990	845	0.854	13.5	56.5	12.44
400	950	820	0.863	13.5	59.5	15.03
450	900	785	0.872	15.5	59.5	18.65
500	830	735	0.886	18.0	63.0	23.83
550	750	665	0.887	18.0	64.0	31.09
600	660	590	0.894	20.5	63.5	38.86

Note: DR is the decrease rate of yield strength in comparison with room temperature yield strength.

The mechanical properties of high strength steels are strongly related to alloy carbides in the microstructure [6]. According to references 9 and 10, the carbides in G4335V steel are M_7C_3 and M_3C when it is tempered at 600°C, and no apparent secondary hardening effect is observed in the G4335V steel. **Table 2** gives the alloy carbides analyzed by XRD in the 3Cr-3Mo steel tempered at 640°C. It can be seen that most alloy carbides are M_2C, which are believed to give rise to strong secondary hardening effect in the 3Cr-3Mo steel [7-8,11]. The contents of each element in the alloy carbides are also listed in table 2, and it is found that the major alloy elements in M_2C carbides are Mo and Cr. It is well recognized that the carbide precipitation during tempering is dependent on diffusion of carbon and alloy elements at the tempering temperature. M_7C_3 is believed to form in some Cr-containing steels at tempering temperature above 400°C, when the diffusivity of Cr is high enough to form Cr-rich carbide. However, the diffusivity of Mo is lower than that of Cr, and therefore it can pronouncedly diffuse only at tempering temperature above 500°C, and the Mo-rich M_2C carbide forms at higher tempering temperatures than Cr-rich M_7C_3 carbide. It is also true that the high-temperature formed M_2C carbide has good tempering softening resistance as well as secondary hardening. The fine M_2C carbides in the martensitic matrix can also be obstructive to the movement of dislocations at elevated temperatures, thus the 3Cr-3Mo steel has lower decrease rate of strength, as shown in figure 1(b).

3.2 Impact toughness

In general, increasing alloy content in low alloy steels may lead to decrease in toughness. It is also reported that some secondary hardening steels containing molybdenum and tungsten appear to have the so-called "secondary hardening embrittlement" and tend to fracture brittlely even at relatively high testing temperature [12-14]. Figure 2 shows the impact energy of the 3Cr-3Mo steel at various test temperatures in the range of −100-300°C. An upper shelf with impact energy of about 70 J and a lower shelf with impact of about 7 J are obtained. The upper shelf appears at test temperature above 50°C, while the lower shelf is in the test temperature range of (−100)-(−80)°C. The room-temperature impact energy is about 36 J, which is much higher than the impact energy requirement for high-strength gun steels. Although the 50% DBTT (Ductile-Brittle Transition Temperature) defined by the test temperature at which the impact energy equal to half the difference between the upper shelf and the lower shelf is about 10°C for the 3Cr-3Mo steel, the fracture surface is still quasi-cleavage even at test temperature of −100°C and no intergranular fracture is found at all, as shown in **figure 3**. It is perhaps because the 3Cr-3Mo steel has high purity and high molybdenum content. Molybdenum can segregate to grain boundary to hinder the segregation of harmful elements such as phosphor, which is proved to be an important factor for intergranular fracture. The fracture surface of the specimen tested at 50°C is composed of dimples, with nonmetallic inclusions such as oxide particles and fine carbides in the center, as shown in figure 3(b).

Table 2 Elemental contents (mass fraction) in alloy carbides in the 3Cr-3Mo steel tempered at 640°C %

Carbides	Fe	Cr	Mo	Mn	Nb	C	N	Total
MX	—	—	0.010	—	0.108	0.006	0.012	0.136
M_3C	0.298	0.260	0.208	0.012	—	0.052	—	0.830
M_2C	0.008	0.491	2.204	0.003	—	0.071	—	2.777
M_7C_3	0.039	0.016	0.001	—	—	0.008	—	0.064

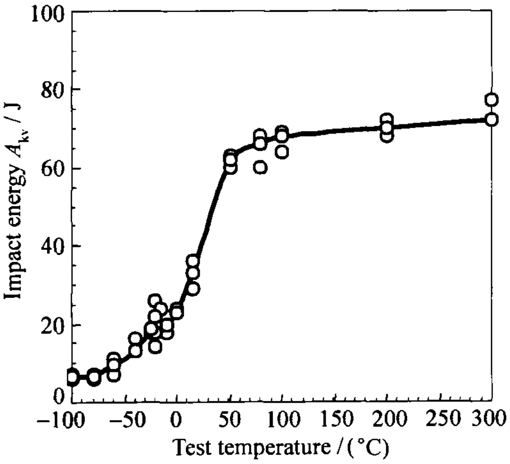

Figure 2 Impact energy of the 3Cr-3Mo steel at various test temperatures.

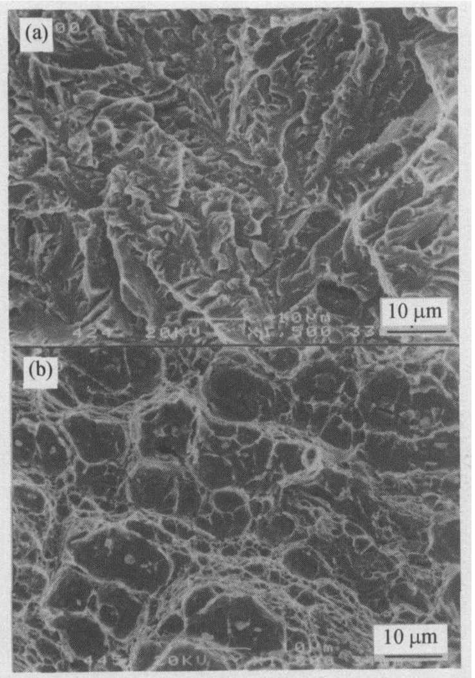

Figure 3 Fractographs of the impact specimens tested at −100°C (a) and 50°C (b), respectively.

From figure 3, it can be seen that the 3Cr-3Mo steel has no secondary hardening embrittlement when it is tempered at 640°C because the impact toughness of the secondary hardening embrittlement steel is very low and the fracture surface is intergranular. It is found to occur in some secondary hardening steels tempered at high temperature with coarse carbides in the microstructure, distributing in the grain boundaries [12]. In the 3Cr-3Mo steel, the M_2C carbides are in fine rod shape, with a diameter of 10-20 nm and a length less than 100 nm even when the tempering time is as long as 600 min, as shown in **figure 4**. It is the fine M_2C carbides that cause tempering secondary hardening without pronouncedly decreasing the toughness. Therefore, the 3Cr-3Mo steel can be used for long-life gun barrel due to its excellent elevated-temperature strength and hardness.

Figure 4 TEM bright field image of the 3Cr-3Mo steel tempered at 640°C for 600 min.

4 Conclusions

(1) The experimental 3Cr-3Mo steel has lower decrease rates of hardness and strength at elevated temperatures compared with normally used Cr-Ni-Mo-V series high-strength gun steels. It is because the 3Cr-3Mo steel has strong secondary hardening effect and high tempering softening resistance, due to the precipitation of fine M_2C carbides at high-temperature tempering.

(2) The impact toughness of the experimental steel at room temperature is much higher than the requirement for normal high-strength gun steels and the steel has no secondary hardening embrittlement at elevated temperatures when it is tempered at 640°C. Even at the test temperature of −100°C, the impact specimen has quasi-cleavage fracture surface and no intergranular fracture is observed.

(3) The 3Cr-3Mo steel is suitable for long-life high-strength gun barrels due to the combination of high strength and good toughness both at room temperature and at elevated temperatures.

References

[1] S. Sopok, P. O'Hara, and G. Pflege, *et al.*, Unified computer model for predicting thermochemical erosion in gun barrels [J], *J. Propulsion Power*, 15(1999), No.4, p.601.

[2] E. Troiano, *Applications of Advanced Materials to Cannon Production* [R], AD-A261699, 1992.

[3] G.N. Vigilante, A. Fish, and G.P. O'Hara, *et al.*, *Elevated temperature Properties of Steels* [R], AD-A317919, 1996.

[4] R.S. Zhang, Modern high strength gun steels [J], *Ordnance Mater. Sci. Eng.* (in Chinese), 18(1995), No.3, p3.

[5] T. Okuno and Y. Tamura, Trends of hot working tool steels in recent years [J], *Iron Steel* (in Japanese), 79(1993), No.9, p.1.

[6] X.T. Wang, *Metal Materials Science* [M] (in Chinese), The Mechanical Industry Press, Beijing, 1987, p.142.

[7] M.Q. Wang, H. Dong, and Q. Wang, *et al.*, Effect of austenitizing on microstructure and mechanical properties of 3Cr-3Mo-Nb secondary hardening steel [J], *Ordnance Mater. Sci. Eng.* (in Chinese), 25(2002), No.5, p.9.

[8] M.Q. Wang, H. Dong, and Q. Wang, *et al.*, Microstructure and mechanical properties of tempered 3Cr-3Mo secondary hardening steel [J], *Iron Steel* (in Chinese), 38(2003), No.3, p.38

[9] J.X. Zhong, X.H. Zheng, and Z.R. Xu, Carbides in steel 4335V [J], *Acta Metall. Sinica* (in Chinese), 25(1989), No.1, p.A31.

[10] A.D. Gingell, H.K.D.H. Bhadeshia, and D.G. Jones, *et al.*, Carbide precipitation in some secondary hardened steels [J], *J. Mater. Sci.*, 32(1997), p.4815.

[11] F.B. Pickering, *Physical Metallurgy and the Design of Steels* [M], Applied Science Publishers Ltd, London, 1978, p.133.

[12] K.B. Lee and H. Kwon, Fracture behavior of secondary hardening steels [J], *Scripta Metall. Mater.*, 27(1992), No.10, p.1355.

[13] H. Kwon, C.M. Kim, and K.B. Lee, *et al.*, Effect of alloy additions on secondary hardening behavior of Mo-Containing steels [J], *Metall. Mater. Trans. A*, 28A(1997), No.3, p.621.

[14] K.B. Lee, H.R. Yang, and H. Kwon, Effect of alloying additions and austenitizing treatments on secondary hardening and fracture behavior for martensitic steels containing both Mo and W [J], *Metall. Mater. Trans. A*, 32A(2001), No.7, p.1659.