Research Article

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Research on high-temperature mechanical properties of wellhead and downhole tool steel in offshore multi-round thermal recovery

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Abstract: High-temperature tensile tests at 25, 150, 250, and 350°C were carried out on 30CrMo, 42CrMo, 1Cr13, and 304 steels. The changes in tensile strength, yield strength, elongation, and area reduction ratio with temperature were determined. By analyzing the fracture morphology and the relationship between strength and hardness, the influence of high-temperature mechanical properties on crack sensitivity and the mechanism of crack formation is discussed. Experimental results indicated that both the tensile and yield strengths of the four steels gradually decrease with the increase in temperature. The yield ratios of 30CrMo, 42CrMo, 1Cr13, and 304 steels are, respectively, 0.71–0.77, 0.79–0.86, 0.84–0.88, and 0.33–0.40 which shows that among the four steels, 304 has the best ductility, while 1Cr13 has the worst ductility. As for the four steels, the values of reduction ratio of area are greater than 60%, except for 42CrMo which is slightly lower than 60% at 150 and 250°C, indicating that the four steels have low crack sensitivity within the test temperature range. Ductile fracture is the main fracture mechanism for 30CrMo, 42CrMo, and 304 steel, whereas brittle fracture is predominant for 1Cr13. There is a linear regression relationship between the strength and hardness at different temperatures. The obtained linear regression relationship can be used to

predict and estimate the strength of 30CrMo, 42CrMo, 1Cr13, and 304 steels at different temperatures according to the hardness results.

Keywords: high-temperature mechanical property, micro-hardness, tensile strength, ductility, fracture morphology

1 Introduction

As the world's most recognized effective method for heavy oil recovery, thermal recovery can further increase crude oil recovery and reverse the current situation of low recovery [1]. The development of thermal recovery wellhead and downhole tools is an important part of offshore heavy oil thermal recovery technology. Therefore, it is imperative to study and test the core technologies and key supporting tools for thermal recovery [2,3].

Stainless steels are usually used as tool steels for acid-resistant valves in petrochemical industry due to their high strength, welding ability, and high corrosion resistance [4,5]. 30CrMo and 42CrMo are low-alloy and high strength alloy steels with Cr and Mo as strengthening elements [6]. In addition to high strength, they also have high toughness and ductility. Therefore, they can be used as high pressure flange, oil drilling pipe, and brake disc in oil recovery industry [7,8].

The valve is frequently subjected to friction and impact in the process of opening and closing. Similarly, the surface temperature of the brake disc rises sharply due to severe friction during braking. Consequently, cracks were easily produced on the valve sealing surface and brake disc due to the great thermal stress caused by huge thermal load. Thus, the reliability of valve and brake disc is greatly affected, and even their service life will be seriously shortened. Therefore, through the research work on the high-temperature mechanical properties of tool steels, the high-temperature ductility and strength vs. temperature curves can be obtained and the brittle transition zone can also be found. Thereby, preventive measures can

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be taken in equipment design and process operation to prevent cracks of wellhead and downhole tool steels in offshore multi-round thermal recovery process.

Crack sensitivity is directly related to high temperature mechanical properties, such as tensile strength, ductility, and hardness [9]. The crack sensitivity will be reduced if the steel has high tensile strength and good ductility at high temperatures. There are great differences at high-temperature mechanical properties of different kinds of steels.

Based on the above discussions, a series of high-temperature performance tests was carried out on 1Cr13 martensitic stainless steel, 304 austenitic stainless steel, 30CrMo alloy steel, and 42CrMo alloy steel in the present work. Tensile and microhardness tests were carried out for the four kinds of specimens at 25, 150, 250, and 350°C, and the relation between strength, ductility, and temperature changes was obtained. By analyzing the fracture morphology and the relationship between strength and hardness, the influence of high-temperature mechanical properties on crack sensitivity and the mechanism of crack formation is discussed. The results of this study can deepen the understanding of high-temperature mechanical behaviors of these four steels, provide important reference data for the application as wellhead and downhole tool steels in offshore multi-round thermal recovery industry, and has certain practical significance.

2 Experimental methods

2.1 Materials and specimen preparation

The materials used in the present research are 30CrMo, 42CrMo, 1Cr13, and 304 steels, and their chemical compositions are shown in Table 1. Before the experiment, 30CrMo, 42CrMo, and 1Cr13 steels were quenched and tempered, while 304 steel was solid-solution treated. The detailed heat treatment conditions for samples are listed in Table 2.

Table 2: Detailed heat treatment conditions for samples

Materials	Heat treatment
30CrMo	850°C oil quenching and tempering (560°C, 5 h)
42CrMo	840°C oil quenching and tempering (480°C, 5 h)
1Cr13	960°C oil quenching and tempering (700°C, 2 h followed by water cooling)
304 steel	Solid-solution treated at 1,050°C for 30 min followed by water cooling

The tensile test specimens were prepared as a round bar with diameter of 16 mm and length of 120 mm according to GB/T 4338-2006. The tensile experiments were carried out at least three times with parallel specimens to ensure good repeatability. The samples with the size of 25 mm × 25 mm × 10 mm were used for microhardness test.

2.2 High-temperature tensile test and microhardness test

High-temperature tensile tests were carried out on the Gleeble 1500D high-temperature tensile testing machine (DSI Company, America). The basic data of yield strength, tensile strength, elongation and reduction of area at 25, 150, 250, and 350°C are obtained. Three parallel tests were carried out at each temperature. After the experiment, the fracture surface was cleaned with alcohol using ultrasonic. The macro morphology of the fracture surface was observed by taking photos and then the micro-morphology of the fracture surface was observed by a JSM 7500F JEOL scanning electron microscope (SEM).

The surface of the specimens for microhardness test was ground step by step with SiC sandpaper up to 2,000 grit and then polished to a mirror finish with 1.5 μm Al₂O₃. Microhardness testing was conducted using a high-temperature Vickers hardness testing machine (ZONE-DE, China) under a 5 kg load for 1 min at 25, 150, 250, and 350°C. Tests were made at random points on the surface, at least five measurements were made at each point to get the average value, and three parallel tests were carried

Table 1: Chemical compositions of 30CrMo steel, 42CrMo steel, 1Cr13 steel, and stainless steel 304 in wt%

Materials	C	Si	Mn	P	S	Cr	Ni	Mo	Cu	Fe
30CrMo	0.26	0.17	0.40	0.025	0.025	0.80	0.35	0.15	0.20	Bal.
42CrMo	0.40	0.23	0.63	—	—	1.02	0.02	0.16	—	Bal.
1Cr13	0.15	1.00	1.00	0.03	0.03	12.0	0.60	—	—	Bal.
304	0.04	0.45	1.18	0.03	0.003	17.24	8.11	—	—	Bal.

out for each type of steel. The temperature is set according to the experimental requirements, and the temperature of the heating furnace is raised at an increment of $10^{\circ}\text{C}\cdot\text{min}^{-1}$ until it reaches the test temperature where it is maintained for 20 min. After the test, the instrument is turned off when the sample drops to the appropriate temperature, and the sample is taken out when it cools to room temperature.

3 Results and discussion

3.1 High temperature stress–strain curve of materials

30CrMo, 42CrMo, 1Cr13, and 304 steels were subjected to tensile tests at 25, 150, 250, and 350°C , and the stress–

strain curves obtained are shown in Figure 1. It can be seen from Figure 1 that the yield stress of the four steels decreases with the temperature increment and the plastic deformation starts at lower stresses. The yield stress and the overall stress–strain curve tend to decrease.

From Figure 1, it can be seen that the stress–strain curves of the four studied steels can be divided into two stages in the whole deformation process at 25, 150, 250, and 350°C . Now 304 steel is taken as an example to discuss in detail. In the first stage, the curve experienced a process of sudden rise and fall. This indicates that severe twinning deformation occurs at the initial stage of deformation [10]. The strain is between 0 and 5%. When the strain is about 40% (150, 250, and 350°C) and 50% (25°C), the stress reaches the peak value and the dynamic recrystallization begins. Previous studies considered that the peak stress during deformation is the initial point of equilibrium between hardening caused by dislocation stacking

Figure 1: Stress–strain curves of 30CrMo, 42CrMo, 1Cr13, and 304 steel at 25, 150, 250, and 350°C (including the summary of yield strength- σ_s , tensile strength- σ_b , and elongation).

Figure 2: Stress-strain curve of 304 steel at 350°C.

and softening caused by dynamic recrystallization [11,12]. While in the second stage, when the strain is between 5 and 40% (150, 250, and 350°C) or 5–50% (25°C), the deformation enters the softening stage, and the dynamic recrystallization is dominant. When the strain reaches 40–50% (150, 250, and 350°C) or 50–65% (25°C), the curve drops suddenly and the sample is fractured.

Figure 2 presents the stress-strain curve of 304 steel tensile specimen at 350°C. In the initial part of the stress-strain curve, Hooke's law is obeyed in the small strain stage, that is, the stress is proportional to the strain. With the increase in strain, the specimen deviates from the linear ratio, which is called the proportional limit. This nonlinearity is usually related to the stress-induced “ductility” flow in the specimen. At this stage, the molecules or microstructure inside the material rearrange or adjust, and

the atoms move to a new equilibrium position. When the strain exceeds the proportional limit, it continues to increase and strain hardening occurs.

3.2 High temperature thermal strength

Figure 3 presents the yield strength and tensile strength of 30CrMo, 42CrMo, 1Cr13, and 304 at 25, 150, 250, and 350°C. It can be seen from Figure 3 that as the temperature increased, the yield strength and tensile strength of the four tested steel specimens presented a decreasing trend. That is, the higher the temperature, the lower the yield strength of the steel. This may be due to the fact that as the temperature rises, the internal energy of the atom increases, which intensifies the atomic motion, thereby reducing the bonding force between the metal atoms, causing the strength of the experimental steel to decrease.

At four test temperatures of 25, 150, 250, and 350°C, the yield ratios of 30CrMo, 42CrMo, 1Cr13, and 304 are, respectively, 0.71–0.77, 0.79–0.86, 0.84–0.88, and 0.33–0.40. Low yield ratio means that the steel has better ductility [13,14]. On the contrary, high yield ratio indicates that the material has strong deformation resistance and plastic deformation is not easy to occur. Among the four steels, 304 steel has the best ductility, while 1Cr13 has the worst ductility.

3.3 High-temperature ductility

High-temperature ductility of metal materials refers to the maximum ability to produce permanent deformation without damage under the action of external force under

Figure 3: Strength curves of 30CrMo, 42CrMo, 1Cr13, and 304 steels at 25, 150, 250, and 350°C: (a) yield strength and (b) tensile strength.

Figure 4: Elongation and reduction ratio of area curves of 30CrMo, 42CrMo, 1Cr13, and stainless steel 304 at 25, 150, 250, and 350°C: (a) elongation and (b) reduction ratio of area.

high temperature, and is usually expressed by elongation after fracture and reduction ratio of area [15,16]. Figure 4 illustrates the elongation and reduction ratio of area curves of 30CrMo, 42CrMo, 1Cr13, and 304 steels at 25, 150, 250, and 350°C. It can be seen from Figure 4a that the elongation at break of stainless steel 304 and 1Cr13

showed a downward trend with increasing temperature, while the elongation at break of 30CrMo and 42CrMo first decreases at 150°C and then increases at 250°C and 350°C than the elongation after breaking at normal temperature. At 150°C, the elongation at break of 42CrMo was the smallest 14.5%. At 250 and 350°C, the elongation at

Figure 5: Macroscopic morphology of fracture of 30CrMo after high-temperature tensile test: (a) 25°C, (b) 150°C, (c) 250°C, and (d) 350°C.

break of 1Cr13 was the smallest, were 17.5 and 15%, respectively. Figure 4b indicates that the reduction ratio of area of 304 steel with temperature is similar to that of 1Cr13, and its reduction ratio of area first became larger at 150°C and then continuously shrinks, while the reduction ratio of area of 42CrMo varies with temperature. The reduction ratio of area of 30CrMo was similar to 42CrMo, both continued to decrease at 150°C, and then continued to increase. At 150°C and 250°C, 42CrMo had the smallest reduction ratio of area and stainless steel 304 had the largest, while at 350°C, 1Cr13 had the smallest reduction ratio of area and 30CrMo had the largest.

As compared with 304 and 1Cr13 stainless steels, 30CrMo and 42CrMo alloy steels have higher carbon content. In the process of high-temperature ductility deformation, retained austenite with high carbon content has large lattice strain, which leads to transformation-induced plasticity effect on the plasticity deformation behavior of lath martensite [12,16]. Therefore, at high temperatures such as at 250 and 350°C, the ductility of 30CrMo and 42CrMo alloy steels increases. Among the four studied steels, 304 steel with the highest nickel content has the best ductility. This is because nickel not only

has the ability of austenitizing but also can stabilize the ductility and toughness of steel at high temperatures [17].

Generally, for steels, the larger the reduction ratio of area value is, the more likely they are to resist external forces without cracks. According to previous research results [7,8], when the reduction ratio of area is greater than 60%, the crack sensitivity will be greatly reduced and the possibility of cracks will be greatly reduced. As for the four tested steels, the values of reduction ratio of area are greater than 60%, except for 42CrMo which is slightly lower than 60% at 150 and 250°C. The results indicated that the four steels have low crack sensitivity within the test temperature range, and all the four steels can be used as wellhead and downhole tool steels in offshore multi-round thermal recovery process.

3.4 Fracture morphology

Macroscopic morphologies of fracture surfaces of 30CrMo, 42CrMo, 1Cr13, and 304 after high temperature tensile tests are shown in Figures 5–8, respectively. Figure 5 is a macroscopic morphology of fracture of 30CrMo. It can be clearly

Figure 6: Macroscopic morphology of fracture of 42CrMo after high-temperature tensile test: (a) 25°C, (b) 150°C, (c) 250°C, and (d) 350°C.

Figure 7: Macroscopic morphology of fracture of 1Cr13 after high-temperature tensile test: (a) 25°C, (b) 150°C, (c) 250°C, and (d) 350°C.

seen that the macrofracture is divided into three parts: fiber zone, radiation zone, and cut lip zone, showing typical ductile fracture with severe necking. With the increase in temperature, the phenomenon of necking around the fracture will be more obvious, indicating that 30CrMo steel has better high temperature toughness and better ability to resist crack growth. At 25 and 150°C, there is no obvious oxidation on the fracture surfaces of 30CrMo. While at high temperatures of 250 and 350°C, the surfaces of the tensile specimen show obvious oxidation phenomenon. Especially at 350°C, the oxidation phenomenon is more obvious, and the surface of fracture is blue.

The result of macroscopic morphology of fracture of 42CrMo is shown in Figure 6, which is different from the result in Figure 5. The degree of necking around the fracture decreased in the initial stage and then increased with temperature increase. Section of fracture has a lot of crack at room temperature, which is owing to the deformation of interface of two adjacent heterogeneous particles into the crack, and the sample performed to its best ability at 350°C. 42CrMo steel also displays high-temperature oxidation under both 250 and 350°C.

Figure 7 presents the macroscopic morphology of fracture of 1Cr13, showing completely opposite result compared to Figure 6. The necking around the fracture is increased in the initial stage, and then decreased with the temperature increase, but the same point is the crack was observed under both 25 and 150°C, and high temperature oxidation was observed under both 250 and 350°C.

Figure 8 reveals the result of macroscopic morphology of fracture of 304 steel. Cracks are not detected and 304 steel shows the best high-temperature toughness at 250°C. The fiber zone of 30CrMo steel has lots of isometric hole, and the surface of the fracture is relatively rough, but surface of 304 steel, 1Cr13 steel, and 42CrMo are relatively smooth.

Figure 9 illustrates the microscopic morphology of fracture of 30CrMo, 42CrMo, 1Cr13, and 304 steel at 350°C. As shown in Figure 9a, the microscopic morphology of 30CrMo has numerous microcracks and is microporous, the tensile fracture is microporous polymerized. Thus, the fracture mechanism of 30CrMo is ductile fracture. It can be seen from Figure 9b that there are many microcracks on the

Figure 8: Macroscopic morphology of fracture of 304 steel after high-temperature tensile test: (a) 25°C, (b) 150°C, (c) 250°C, and (d) 350°C.

Figure 9: The microscopic morphology of fracture at 350°C: (a) 30CrMo, (b) 42CrMo, (c) 1Cr13, and (d) 304 steel.

Figure 10: Microhardness of 30CrMo, 42CrMo, 1Cr13, and stainless steel 304 at 25, 150, 250, and 350°C.

tensile fracture surface. When plastic deformation occurs, the grains move along the sliding surface of the matrix, and inclusion particles hinder the sliding behavior. As the strain changes, the number of dislocations increases, and the effect of stress concentration is obvious. When the stress acting on the inclusion reaches or exceeds the strength that the inclusion can bear, the inclusion will be broken or separated from the interface, and the initial microcracks will be formed. However, the fracture morphology of 1Cr13 shown in Figure 9c after tensile is tool tip type. The concentration of thermal stress lead to the growth of microcracks along the tips and gradually develop into cracks, causing fracture ultimately. So for 1Cr13, the fracture mechanism is mixed with ductile fracture and brittle fracture, while brittle fracture is predominant. Figure 9d shows that there are many microporosities and dimples on the fracture surface. The fracture surface of 304 is extremely rough, and the SEM photos show some clear and some

Figure 11: Relationship between strength (yield strength and tensile strength) and microhardness at 25, 150, 250, and 350°C.

Table 3: Relationships between strength and hardness of 30CrMo, 42CrMo, 1Cr13, and 304 steels

Materials	Relationships between yield strength and hardness	Relationships between tensile strength and hardness
30CrMo	Yield strength = $2.63 \times HV_5 - 247.33$	Tensile strength = $2.03 \times HV_5 + 100.87$
42CrMo	Yield strength = $3.85 \times HV_5 - 410.54$	Tensile strength = $2.94 \times HV_5 + 43.32$
1Cr13	Yield strength = $2.85 \times HV_5 - 3.11$	Tensile strength = $4.20 \times HV_5 - 233.37$
304 steel	Yield strength = $0.95 \times HV_5 + 59.32$	Tensile strength = $1.66 \times HV_5 + 274.36$

fuzzy morphology. Dimple is the main microscopic feature of metal ductile fracture [18]. Dimples are indicative of the microcavities after coalescence, while deep dimples represent high ductility of the material [19,20]. Similarly, the uneven fracture surface is also the manifestation of high ductility of steels. Therefore, ductile fracture is the main fracture mechanism for 304 steel.

3.5 High-temperature microhardness

Figure 10 shows the Vickers microhardness of 30CrMo, 42CrMo, 1Cr13, and 304 at 25, 150, 250, and 350°C. It can be seen that the Vickers hardness of the four steels decreases with the increasing temperature. The hardness of 30CrMo, 42CrMo, 1Cr13, and 304 steel at 350°C are, respectively, 12.40, 9.36, 15.98, and 47.39% lower than those at 25°C. The relationship between the temperature and microhardness will be in a negative correlation, that is, the higher the temperature, the lower the hardness.

At high temperatures, the hardness of 304 steel is only 105 HV₅. Because of its relatively low hardness and poor wear resistance, it is limited as a key moving part under friction condition in the application of offshore multi-round thermal recovery. With consideration of the single factor of high-temperature hardness, 30CrMo, 42CrMo, and 1Cr13 are recommended for use as wellhead and down-hole tool steel.

Generally, there is a certain relationship between the strength and hardness of steels. The higher the strength, the higher the hardness [21,22]. The hardness and strength of steels are two random variables due to the individual local subtle differences. Although they are usually proportional to each other, they cannot be expressed by ordinary functional relationship. The hardness test method is simple and easy and will not damage the specimen, and has a certain relationship with the strength. Therefore, in practical engineering applications, the hardness test method is often used to estimate the strength of steels [23]. According to the strength and hardness data obtained from the test, the relationships between yield strength, tensile strength, and hardness are established by using linear regression

method with Origin software [24], as shown in Figure 11. It can be seen from the results in Figure 11 that there is a linear regression relationship between the strength and hardness of 30CrMo, 42CrMo, 1Cr13, and 304 at different temperatures. The relationships between the strength and hardness of 30CrMo, 42CrMo, 1Cr13, and 304 steels at different temperatures can be expressed by the following equation:

$$\text{Strength} = K_1 \times HV_5 + K_2, \quad (1)$$

where Strength is the yield strength or tensile strength of the steels, HV₅ is the microhardness value of the steels, K_1 is a proportional coefficient, and K_2 is a constant. The proportional coefficient K_1 is an empirical constant which is independent of temperature and depends on the properties of the material itself. The detailed values of K_1 and K_2 are listed in Table 3. The obtained linear regression relationship can be used to predict and estimate the strength of 30CrMo, 42CrMo, 1Cr13, and 304 at different temperatures according to the hardness results.

4 Conclusion

The main conclusions drawn from the investigation on the high-temperature performance of 30CrMo, 42CrMo, 1Cr13, and 304 steels at 25, 150, 250, and 350°C are:

1. The yield ratios of 30CrMo, 42CrMo, 1Cr13, and 304 are, respectively, 0.71–0.77, 0.79–0.86, 0.84–0.88, and 0.33–0.40 indicating that among the four steels, 304 has the best ductility, while 1Cr13 has the worst ductility.
2. As for the four tested steels, the values of reduction ratio of area are greater than 60%, except for 42CrMo which is slightly lower than 60% at 150 and 250°C, indicating that the four steels have low crack sensitivity within the test temperature range.
3. Ductile fracture is the main fracture mechanism for 30CrMo, 42CrMo, and 304 steel, whereas brittle fracture is predominant for 1Cr13.
4. For the four tested materials, there is a linear regression relationship between the strength and hardness at different temperatures. The obtained linear regression

relationship can be used to predict and estimate the strength of 30CrMo, 42CrMo, 1Cr13, and 304 steels at different temperatures according to the hardness results.

5. Considering the comprehensive influence of strength, hardness, ductility, and crack sensitivity, 30CrMo and 42CrMo steels have excellent high-temperature mechanical properties in the test temperature range. And both 30CrMo and 42CrMo steels can be used as wellhead and downhole tool steel in offshore multi-round thermal recovery.

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