Study on the Mechanical Properties of 125S Casing for oil and gas wells

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Abstract. In the process of evaluating the quality of a batch of 125S casing for oil and gas wells, it was found that the mechanical properties of different casing bodies in the same batch were significantly different, and the fluctuation range of yield strength was up to 60 MPa. The steel pipe with the lowest yield strength was not satisfied according to the technical standards. In order to study the causes of the uneven tensile properties, the chemical composition analysis, tensile tests, Charpy impact tests, Rockwell hardness tests and metallographic analysis were investigated for the two casings of this batch. Through the analysis of the test results, it is found that the chemical composition and metallographic structure of this batch of casing were conforming to with the design requirements, and the materials possessed high toughness. The problem of non-uniform performance of this batch casing was generated from the heat treatment stage during the production process. The excessive tempering temperature caused the reduction of material strength.

1. Introduction
In recent years, the problem of energy shortage has become increasingly serious in worldwide. The focus of energy exploitation has gradually shifted to oil and gas fields with high H₂S, CO₂ and other corrosive media. Low-alloy sulfur-resistant casing, dual-phase stainless steel and nickel-based alloy casing have been widely used, while low-alloy sulfur-resistant casing occupies a large proportion. The highest strength of sulfur-resistant low-alloy steel casing in API Spec 5CT is C110, which yield strength requirement is 110 ksi. At present, in order to develop reservoirs with deeper burial, higher pressure and temperature, higher strength acid-resistant pipes are needed. Manufacturing enterprises have done a lot of research on higher-grade sulfur-resistant pipes. Up to now, 125 ksi steel grade casing is the limit of high strength and low alloy anti-acid oil well pipe adapted to moderate acidic environment at present. Higher strength anti-SSC oil or gas well pipe (such as 140 ksi) need to use high alloy material.

As sulfur-resistant casing, it needs not only excellent H₂S corrosion resistance, but also proper mechanical properties matching service conditions. Therefore, mechanical performance evaluation of casing is also needed, including material mechanical properties evaluation and full-scale mechanical properties evaluation. A batch of 125S casing were product to be used as sulfur-resistant casing, and the mechanical properties were evaluated. It was found that the mechanical properties of different casing bodies in the same batch were obviously different, the fluctuation range of yield strength was up to 60 MPa. The lowest yield strength was only 818MPa. According to the technical standards, the yield strength of 125S grade should be higher than 852 MPa and below 965 MPa, which meant that
the lowest yield strength of this batch casing was not satisfied. In order to investigate the causes of properties fluctuation, a series of experiments and analyses were carried out, and the influence of steel pipe manufacturing process on mechanical properties was also discussed.

2. Test methods and results

Test specimens were Φ177.80mm×12.65mm 125S casing pipe bodies. Two specimens were taken from two different pipe of the same batch of casing, which marked as 1# and 2# respectively. Chemical composition analysis, mechanical properties testing, metallographic analysis were made on the two specimens.

2.1. Chemical Composition Analysis

The samples were respective taken from 1# specimen and 2# specimen, and analyzed by ARL 4460 analyzer according to standard ASTM A751. The results were listed in Table 1. It was shown that the chemical compositions of the two samples meet the requirements and there is no difference between them, which is the same batch of smelting. The anti-H2S corrosion material has low phosphorus and sulfur content, and is characterized by adding elements niobium, vanadium and titanium to enhance toughness and reduce ductile-brittle transition temperature. More molybdenum elements were added to improve the hardenability and tempering stability of steel, while manganese and chromium elements were moderately added.

Table 1. Chemical composition analysis results (wt.%)

| Specimen No. | C  | Si  | Mn  | P    | S     | Cr  | Mo  | Ni  | Nb  | V  | Ti  |
|--------------|----|-----|-----|------|-------|-----|-----|-----|-----|----|-----|
| 1#           | 0.29 | 0.23 | 0.50 | 0.0070 | 0.00063 | 0.51 | 0.85 | 0.035 | 0.024 | 0.19 | 0.025 |
| 2#           | 0.29 | 0.24 | 0.50 | 0.0075 | 0.00047 | 0.51 | 0.84 | 0.036 | 0.025 | 0.19 | 0.025 |

2.2. Tensile Test

Three tensile samples were taken from each specimen and distributed equidistantly along the circumference of the pipe. The strip tensile samples were 25.4 mm width. According to standards ASTM A370, tensile tests were carried out in room temperature. Three samples were taken from each test section along the same circumference. The tensile test results were shown in Table 2 and Figure 1. The test results of three specimens on the same pipe were at the same level and have good consistency. The test results of different pipes were quite different. The strength difference was up to 60 MPa. The tensile test results of 1# specimen do not meet the requirements. However, the material of the tube had good circumferential homogeneity and obvious material anisotropy or radial inhomogeneity.

Table 2. Tensile properties tests results

| Specimen No. | Location1) | Yield strength2) (MPa) | Tension strength (MPa) | Elongation (%) |
|--------------|------------|------------------------|------------------------|---------------|
| 1#           | 1-a        | 829                    | 886                    | 27            |
|              | 1-b        | 818                    | 884                    | 26            |
|              | 1-c        | 820                    | 883                    | 25            |
| 2#           | 2-a        | 870                    | 920                    | 23            |
|              | 2-b        | 880                    | 935                    | 25            |
|              | 2-c        | 880                    | 935                    | 25            |

Note: 1) Tensile specimens are taken from the same radial position with a distance of 60 degrees. 2) 0.65% total elongation under load yield strength.

2.3. Charpy V-notch test

The size of Charpy V-notch test sample was 10×10×55 mm. According to standards ASTM E23, the Charpy V-notch tests were carried out in room temperature. The Charpy V-notch test results were shown in Table 3. The two specimens have high impact toughness.
Table 3. Charpy V-notch test results

| Specimen No. | Orientation | Sample size, mm | Test temperature, °C | Absorbing energy, J | Single | Average |
|--------------|-------------|-----------------|----------------------|--------------------|--------|---------|
| 1#           | Transverse  | 10×10×55        | 0                    | 138                | 144    | 143     | 142     |
|              | Longitudinal| 10×10×55        | 0                    | 160                | 154    | 150     | 155     |
| 2#           | Transverse  | 10×10×55        | 0                    | 115                | 125    | 120     | 120     |
|              | Longitudinal| 10×10×55        | 0                    | 138                | 143    | 141     | 141     |

2.4. Rockwell C hardness test

According to standards ASTM E18, the Rockwell C hardness test were carried out. Hardness values are lower than HRC 32, meeting the requirements of technical standards.

Table 4. Rockwell C hardness test results

| Test location | Hardness value, HRC | Hardness variation, HRC |
|---------------|---------------------|-------------------------|
| Quadrant I    | 28.5 28.0 29.0      | 1.0                     |
| Quadrant II   | 27.5 26.0 27.0      | 1.0                     |
| Quadrant III  | 27.0 27.5 28.0      | 1.0                     |
| Quadrant IV   | 28.0 28.5 29.0      | 1.0                     |
| Quadrant I    | 30.0 30.5 31.0      | 1.0                     |
| Quadrant II   | 31.0 31.5 30.5      | 1.0                     |
| Quadrant III  | 29.5 30.0 30.0      | 0.5                     |
| Quadrant IV   | 31.0 30.5 31.0      | 0.5                     |

2.5. Metallographic Analysis

Samples were taken from 1# Specimen and 2# Specimen, were analysed according to standards ASTM E45 and ASTM E112. The analysis results were shown in Table 5, and the optical micrographs were shown in Fig. 2. There were a little of non-metallic inclusion in the two specimens.
Microstructure of casing body was tempered sorbite (Figure 2-a, Figure 2-b). The material has lower inclusion content and fine grain size. There was no significant difference between 1# and 2# samples.

Table 5. Metallographic analysis results

| Specimen No. | Non-metallic inclusion | Microstructure | Average grain size |
|--------------|------------------------|----------------|-------------------|
|              | Type A | Type B | Type C | Type D |                  |                 |
|              | Thin   | Heav   | Thin   | Heav   | Thin             | Heav            |                 |
| 1#           | 0.5    | 0      | 0.5    | 0      | 0                | 0.5             | Tempered sorbite | 9.0            |
| 2#           | 0.5    | 0      | 0.5    | 0      | 0                | 0.5             | Tempered sorbite | 9.0            |

3. Discussion

Based on the above test results, it is found that the chemical composition and metallographic structure of these materials meet the design requirements. The problem lies in the mechanical properties. The mechanical properties of 2# samples meet the design requirements, while the tensile properties of 1# samples do not meet the design requirements. In other words, they do not meet the requirements of 125 ksi steel grade.

From the comparison of the mechanical properties test results of 1# and 2#, it is found that the relationship between toughness and hardness conforms to the conventional mechanics, that is, the higher yield strength and tensile strength, the lower toughness and the higher hardness. It has been realized to manufacture casing with good sulfur resistance. Some studies have shown that when the hardness of the material over HRC32, the sulfur resistance of the material will drop sharply, while the hardness is guaranteed at HRC32, the yield strength is often low, or cannot reach the design or production requirements. Through the test results of 2# Specimen, there were shown that its performance meets the production and design requirements of 125S. In order to ensure its sulfur resistance, the yield strength is produced in accordance with the lower limit of requirements.

The radial properties of 1# and 2# specimens are not different, which indicates that the material inhomogeneity is in the axial direction of different steel pipes. Through the analysis of the main production process of casing, this problem occurs in small batch trial production of casing in the same smelting batch and production batch. The reason is not in the rolling process, but in the heat treatment process.

The tensile strength of 125S casing is more than 897 MPa, and the qualified yield strength range is 862 MPa to 965 MPa. The allowable fluctuation range of yield strength is 103 MPa. Compared with other grades in API Spec 5CT, the allowable fluctuation range of yield strength is smaller. For
example, the qualified range of yield strength of Q125 grade is 862 MPa to 1034 MPa, and the allowable fluctuation range is 172 MPa. For example, the qualified yield strength of P110 steel grade ranges from 758 MPa to 965 MPa, and the allowable fluctuation range is 180 MPa. Compared with grade P110, the upper limit of yield strength of grade 125S is identical, but the lower limit is much larger, and the allowable fluctuation range is only 60% of grade P110. Therefore, the heat treatment process of 125S grade will be different from that of P110 or Q125 grade. In the heat treatment process, more strict and precise temperature and time control is needed.

Four heat treatment process elements, quenching temperature, quenching time, tempering temperature and tempering time, are analyzed and divided horizontally to analyze the effect of heat treatment process on tensile strength. Combining with the metallographic analysis results, it is shown that the alloy elements have been evenly distributed in the rolling and quenching process, while in the tempering process, the location of excessive local heating will come out. In the investigation of manufacturing process, it was found that this batch of casing was produced in small batch, and the high tempering temperature is unbalanced. The phenomena of increasing plasticity and toughness and decreasing strength, which is proved that the influence of excessive tempering temperature.

In small batch production, the temperature in the heat treatment furnace is often not very uniform, resulting in a large temperature deviation between the two ends and the middle of the heat treatment furnace, which makes the heating of the pipe uneven. In mass production, the uniform temperature in the heat treatment furnace will greatly reduce the occurrence of this problem. At this time, orthogonal test [5] can be used to further optimize the heat treatment process, so that the material has high strength and good sulfur resistance. The yield strength of the material can be improved according to the lower limit of steel grade requirements, thus reducing the appearance of products whose strength does not meet the requirements.

4. Conclusions and Suggestions
The problem of non-uniform performance of the casing in this batch were come from the heat treatment stage during production. In the process before heat treatment, the alloying elements in the casing pipe have been evenly distributed. The mechanical properties in circumferential position of each casing were uniform. The excessive tempering temperature caused the reduction of material strength and the plasticity and toughness increase.

In production, the heat treatment process should be optimized to keep the temperature in the heat treatment furnace accurate and uniform, and the holding time accurate, so as to reduce the occurrence of unqualified products and greatly reduce the occurrence of uneven tensile properties.

The requirement of API Spec 5CT for grade Q125 is that three different steel pipes should be sampled from the same batch for inspection. The actual factory inspection or acceptance inspection before use should be strictly carried out in accordance with the regulations. The production inspection frequency of 125S steel grade is not lower than API standard requirements and for Q125 grade. The unqualified products should be screened in time and used in downgrading.

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