Effect of heat treatment on property and residual stress of cold drawn tube

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Abstract—The change of strength, toughness and residual stress of Q690 cold-drawn tube were studied under (400 ~600)℃ and heat preservation (1-3)h heat treatment. With the increase of temperature and the extension of the holding time, the strength and residual stress of the cold drawn tube gradually decreased, and the impact toughness increased first and then decreased. When holding at 550 ℃ for 2 hours, the impact toughness reached the highest 34.6J; the mechanical properties of cold drawn tubes were mainly affected by the reduction of internal stress and grain deformation caused by heat treatment.

1. Introduction
Cold drawn tubes were widely used in various industries of the national economy with high precision, low roughness, high strength and other characteristics[1]. In the application of hydraulic cylinders, due to the high precision of cold drawn tubes, the processing hours was greatly reduced and the material utilization was improved[2]. The cold drawing plastic deformation enables the steel pipe to obtain higher strength and dimensional accuracy, but greatly reduces the plasticity and toughness [3], at the same time, a large amount of internal stress is accumulated in the steel pipe, which increased the risk of instability of material size and performance. Therefore, the heat treatment was added to improve the internal stress of cold drawn tube and improve the mechanical properties and dimensional stability. At present, most of the research on cold drawn pipe mainly focuses on the simulation of cold drawing process and the influence of cold drawing deformation ratio on mechanical properties. The internal stress distribution of cold drawn pipe under non-uniform elastic-plastic deformation was studied, which is used to guide the optimal cold drawing process design [4]. The research on the heat treatment of cold drawn tube is relatively few, and the regularity of the influence of heat treatment parameters on the toughness and residual stress of cold drawn pipe is lacking, which can not accurately guide the formulation of heat treatment process in the industrial production of cold drawn pipe. Improper design of the heat treatment process will cause the performance of the cold drawn tube to be low, the bearing capacity of the manufactured cylinder will be weak, and the dimensional accuracy will change after long-term use, which increases the safety risk of the whole product.
In this paper, a heat treatment study of Q690 cold-drawn tube was carried out, and the influence of heat treatment process on the toughness and residual stress of the cold-drawn tube was analyzed in order to discover the performance change and residual stress release rule of the strong texture material under the combined thermal effect of temperature and time, which could provide reference for the heat treatment design of the cold drawn tube and improve the technical level of the oil cylinder.

2. Experiment

2.1 Raw materials
The Q690 hot-rolled tube with outer diameter of 196mm, wall thickness of 17mm and total length of 6000mm was made into the cold drawn tube with outer diameter of 185mm and wall thickness of 12.5mm by the 60t cold drawing machine. Then the cold drawn pipe was sawed into 15 short pipes with 400mm for standby.

2.2 Instrument and equipment
Heat treatment furnace (N41/h), Metallographic microscope (DMI5000M), Universal material testing machine (600KN), Pendulum impact testing machine (PTN2200), Stress detector.

2.3 Research programme

![Heat treatment process](image)

According to the heat treatment process shown in Figure 1, the 400mm long cold drawn tube was put into the heat treatment furnace and raise the temperature to T1 in 1 hour, keep the temperature at T1 for t1, then drops down to 300 ℃ within 1 hour, out of furnace and natural air cooling. The heat treatment temperature and holding time are shown in Table 1. The two key factors of heat treatment temperature and holding time were designed and studied, with each factor is 5 levels and a total of 25 groups of experiments.

| Temperature T1(℃) | 400 | 450 | 500 | 550 | 600 |
|-------------------|-----|-----|-----|-----|-----|
| Soaking Time t1(h)| 1   | 1.5 | 2   | 2.5 | 3   |

The yield strength and impact absorption energy (°C of cold drawn tube before and after heat treatment were tested by universal material testing machine and pendulum impact testing machine; according to GB/T31310-2014 metal material-determination of residual stress-hole drilling strain method, the residual stress of cold drawn tube before and after heat treatment was analyzed by stress detector; the metallographic structure of cold drawn tube was analyzed by metallographic microscope.
3. Results and analysis

3.1 Effect of holding time on properties and stress

In Fig. 2a the yield strength of cold drawn tubes gradually decreases with the extension of holding time in the range of 400°C ~ 600°C, and the decreasing trend tends to be gentle. Holding at 400°C for 1 hour, the yield strength of cold drawn tube decreased the least, about 14 MPa. After holding at 600°C for 3h, the yield strength of cold-drawn tube decreased the most, about 129Mpa.

![Graph a](image1)

![Graph b](image2)

![Graph c](image3)

Fig. 2 Relationship curve of yield strength, impact absorption energy and residual stress affected by holding time

a. yield strength; b. impact absorption energy; c. residual stress

It can be seen from Fig. 2b the impact toughness of the cold-drawn tube gradually increases first and then decreases with the extension of the holding time at a temperature of 400°C to 600°C. Within 400°C ~ 550°C, when the holding time is less than 2 hours, the impact toughness gradually increases...
with the increase of the holding time, otherwise which is more than 2 hours, the impact toughness decreases with the increase of the holding time. At 600℃ for 1.5 hours, the impact toughness turns with the increase of the holding time, which increases first and then decreases. When kept at 550℃ for 2 hours, the impact toughness of the cold drawn tube is the highest, reaching 34.6 J, which is 12.1 J higher than the original state (22.5 J).

From Fig. 2c, it was found that the original main residual stress of the cold drawn tube is -45 Mpa, which is expressed as compressive stress. In the range of 400℃ ~ 600℃, with the extension of the holding time, the residual stress of the cold drawn tube gradually approached from -55 Mpa to 0 Mpa, after holding at 550℃ or 600℃ for 3 hours, the residual stress of the cold-drawn tube appears as a tensile stress close to 0 Mpa.

3.2 Effect of heat treatment temperature on properties and stress

![Graphs showing yield strength, absorbed energy, and residual stress vs. heat treatment temperature.](image)

Fig. 3 Relationship curve of yield strength, impact absorption energy and residual stress affected by heat treatment temperature

a. yield strength; b. impact absorption energy; c. residual stress
The change curve of the yield strength with the heat treatment temperature is shown in Fig. 3a. It can be seen that as the heat treatment temperature increases, the yield strength and residual stress of the cold-drawn tube gradually decreases, and the trend of this decrease is also gradually slowed down. In Fig. 3b, with the change of heat treatment temperature, the impact toughness changed from increasing to decreasing at the holding time of 2 hours.

Compared with Fig.2 and Fig.3, it was found that the heat treatment temperature and holding time have a comprehensive effect on the strength of cold drawn tube. With the increase of temperature and time, the strength and internal stress of the material gradually decrease. The influence of heat treatment temperature on the strength is greater than the holding time. The effect of excessive temperature and long holding time will cause the residual stress to increase in reverse. Within the range of (400-600) °C, (2-5) hours, the impact toughness of the cold drawn tube has a peak, which indicating that the heat treatment temperature and holding time have an incomplete gain effect on the impact toughness. Similarly, too high temperature or too long holding time will lead to the decrease of toughness.

3.3 Effect of heat treatment process on Microstructure

Fig. 4 shows the metallographic structure of cold drawn tube in the cold drawing state and the different heat treatment state. Which could found that the metallographic structure of cold drawn tube is ferrite and pearlite in original state and after different heat treatment, which is distributed in strip structure.

In Fig.4a, it was found that after the cold-drawn plastic deformation of the Q690 hot-rolled tube, the ferrite grains become more slender along the drawing direction, part of the ferrite grains are broken, and the ferrite and cementite are seriously interlaced. Compared with Figures 4a-4f, it can be seen that with the increase of temperature and time effects, the metallographic structure still shows the band structure distribution of ferrite and pearlite, but the elongated ferrite grains gradually change to equiaxed grains, the distorted grains gradually reduced, and the degree of banding was reduced.
4. Comprehensive
During the cold drawing plastic deformation process of Q690 hot rolled tube, due to the different hardness of ferrite and cementite in the material, the grain deformation under stress is different. The extruded softer ferrite grows longer in the drawing direction, and the harder cementite is partially embedded inside the ferrite to form a staggered structure. As a result, the grain boundaries of multiple grains are squeezed and moved, which increases the grain deformation and lattice distortion, improve the dislocation density, and finally advance the grain sliding deformation resistance. In the metastable state, the strength of the material increases and the toughness and plasticity decrease. At the same time, a large amount of internal stress is accumulated at the grain boundary and dislocation, which makes the material in the metastable state.

When the cold drawn tube is put into the heat treatment equipment, as the increase of temperature and holding time, under the amount of energy the deformed grains gradually transform into equiaxed grains. The change of grain boundary caused by grain recovery deformation rearranges the entangled dislocations in the material, thus reducing the number of dislocations. The elastic distortion energy inside the material is reduced. Eventually, the internal stress of the cold drawn tube is reduced and tends to be uniform, the part changes from a metastable state to a stable state [5]. The decrease in the strength of the cold-drawn tube is mainly caused by the recovery of the internal grain deformation and the reduction of the dislocation density. The reason for the reverse increase of residual stress after the reduction to the minimum may be due to the uneven thermal expansion and contraction of ferrite and cementite under the action of temperature. At the same time, when the temperature and time effects are too large, the uneven growth of ferrite and cementite grains will also cause the increase of internal stress.

Impact toughness is the ability of a material to absorb plastic deformation work and fracture work under impact load, which is affected by the chemical composition, smelting method, metallographic structure, internal defects and environmental temperature. The significant growth of ferrite grains will reduce the impact toughness of materials [6]. The research on the relationship between the fine grain ratio of weld seam structure and impact toughness also shows that the impact toughness of the material is higher, when the content of fine crystal structure is higher [7].

After cold drawing plastic deformation, all the grains distribute along the drawing direction and become slender. Under the same stress the deformation degree of ferrite and cementite is different, which results in the change of grain boundary binding force, finally leads to the decrease of toughness of the material after cold drawing. After holding at (400-600) °C for a period of time, the deformed grains recover and transform to equiaxed grains. The orientation effect of cold drawing is weakened, but it is not enough to eliminate the effect of cold drawing. Therefore the impact toughness is improved to a certain extent, it is difficult to reach the toughness before cold drawing. After heat treatment, the impact toughness of the cold drawn tube increases first and then decreases. There are may be two reasons, the first point is that the excessively high temperature and holding time cause the grain size to increase, which causes the impact toughness to decrease; the second point is due to the dislocation decreases, the impact crack propagation resistance is reduced, resulting in a reduction in impact toughness.

5. Conclusions
In the temperature range of (400-600) °C, with the increase of heat treatment temperature and holding time, the yield strength and residual stress of Q690 cold drawn tube gradually decrease, and the heat treatment temperature has a great influence on the strength.

The impact toughness of Q690 cold drawn tube increases first and then decreases under the effect of temperature and time. When kept at 550 °C for 2 hours, the impact toughness of cold drawn tube is the highest, about 34.6J, which is an increase of about 50%.

Through heat treatment, the internal stress of the cold drawn tube is reduced, the grain distortion and the dislocation density are weakened, and the cold drawn tube changes from metastable state to steady state.
References

[1] Liu Jian-fang. Application of High Accuracy Cold Drawing Tech.in Geological Pipe Process[J]. Exploration Engineering(Rock & Soil Drilling and Tunneling) 2006 33 (4): 44-45.

[2] Wang Gui-xia, He wei. Application of Technique of the Cold Drawing Precise Steel Pipe in Hydraulic Cylinder of Construction Machinery[J]. Chinese Hydraulics & Pneumatics 2003(2):44-45.

[3] Zhang Jing, Luo Hai-xia, Ye Hai-yan. Application of XYQ420 Cold Drawn Tube for Cylinder casting[J]. Hydraulics Pneumatics & Seals 2016(4):55-56.

[4] Ye Jinduo Wen Dian-ying. Analysis of the process of the non-mandrel pipe by non-liner finite element[J]. Heavy Machinery 2001(6):41-44.

[5] Li Wentao, Lin Zhen-ming. Study on residual stress evolution of cold-rolled strip in annealing process [J]. Shanghai Metals 2016 38(1):42-46.

[6] Yang Gang, Liu Zheng-dong. Effect of Heat Treatment on Impact Toughness of Heat-Resistant Steel ЭP866[J]. Journal of Iron and Steel Research. 2002 14(5):30-34.

[7] Li Wen-bin, Jiang Yun-jian. Study on relationship between occupancy of fine grain and impact toughness of P92 steel welding seam[J]. Electric Welding Machine 2010 40(7):60-62.