Test and Analysis on Peeling and Cracking on Surface of 45 Steel Shafts

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Abstract. Aiming at the peeling and cracking appear on the surface of a 45 steel shaft after surface quenching and grinding, we’ve conducted chemical composition analysis, hardness test and metallographic microstructure analysis for the cracked shaft sample. The results shows that the main reason for the peeling and cracking of 45 steel shafts is the stress generated due to the uneven structures produced on the surface during quenching and tempering after forging and surface quenching.

1. Problem
As a kind of quality carbon structural steel used for manufacturing shaft parts, 45 steel has high strength, certain degree of plasticity and toughness and good machinability, and can get good comprehensive mechanical properties after quenching and tempering. While in actual manufacturing process, steel parts are prone to form various cracks after quenching and processing due to multiple factors, and the condition is difficult to control and will lead to increased rejection rate. A shaft, with diameter of 130mm, manufactured by XXX company and made of 45 steel, has the following processing steps: casting – forging – (rough machining) – quenching and tempering – finish machining – surface quenching – low temperature tempering – grinding. In actual manufacturing, cracking occurs on the shaft during the storage after grinding, with the macro appearance of cracks shown in figure 1. It can be concluded from observations that most cracks appear on the thin layer on the surface, with thickness of about 0.3mm-0.5mm, and cracks are generally in parallel to the surface of parts and have large area, acting as the direct reason for surface peeling. Some workpieces have secondary cracks along axial direction, some even have tertiary cracks along tangential direction. To probe into the reason for shaft cracking, we’ve conducted in-depth and detailed tests on material of parts, microstructure, heat treatment process, etc. as well as research works such as chemical composition analysis, hardness test and metallographic microstructure analysis, aiming to provide effective ways to deal with failures of shafts.
2. Methods and steps for test research

2.1 Sampling
Take samples with length of 50mm-60mm from shafts and conduct material analysis and original structure analysis.

2.2 Test research
Conduct chemical composition analysis, hardness test and metallographic structure analysis, etc. on the sample and research into the influence of shafts’ material, structures and mechanical property on generation of cracks based on characteristics of cracks.

2.3 Results analysis
Analysis results, conclude reasons for generation of shaft cracks and its spreading rules, and propose methods and measured to prevent cracks.

2.4 Major instruments and equipment used
Spectrum analyzer, Rockwell hardness tester, P-2 type metallographic microscope and S-530 type scanning electron microscope (SEM).

3. Test research results and analysis

3.1. Chemical composition analysis
By applying the spectrum analyzer, we’ve conducted chemical composition analysis for the shaft samples with cracks, determined the major chemical compositions of shafts, analyzed the materials of shaft materials as well as possible influencing factors. The analysis result is shown in table 1. The result shows that the chemical composition of the steel used for manufacturing the shaft meets the technical requirements for the 45 steel in accordance with GB699-88 Quality Carbon Structure Steel – Technical Requirements.

| Element                | C     | Si   | Mn    | P     | S     | Cr  |
|------------------------|-------|------|-------|-------|-------|-----|
| Content (%)            | 0.47  | 0.26 | 0.65  | 0.027 | 0.021 | 0.16|
| Content stipulated in GB699-88 (%) | 0.42 – 0.50 | 0.17 – 0.37 | 0.50 – 0.80 | ≤0.035 | ≤0.035 | ≤0.25 |
3.2 Hardness test
The picture for section of the sample is shown in figure 2. The white highlighted area on the periphery is the hardened layer. The shaft has gone through surface quenching with a hardened layer thickness of about 3mm. We measured hardness of the surface and core of shaft by conducting Rockwell hardness test, with test results shown in table 2.

Table 2. Hardness test results.

| Location                      | Quench hardened layer on surface | (The core is located at about 20mm from the surface) |
|-------------------------------|---------------------------------|------------------------------------------------------|
| Measured hardness value       | 55.5, 56.3, 55.5, 51.7          | 11.2, 13.4, 12.1, 10.3, 13.0, 12.6, 11.6, 12.6, 12.1 |
| Average hardness value        | 54.7                            | 12.1 (≈192HB)                                       |

After surface quenching of the shaft, the surface is the quenching structure, while the core goes through quenching and tempering treatment, so the surface and the core have different microstructure and thus definitely have different hardness values. It can be concluded from table 2 that the average hardness value of the quench hardened layer on surface is HRC54.7, the core hardness is HRC12.1 (20mm from the surface), which is about HB192 in terms of Brinell hardness. The surface hardness is relatively high, and the core hardness is relatively low, demonstrating huge difference between the two values.

4. Metallographic structure and analysis

4.1 Core structure
According to documents introduction [1], the cooling period of quenching for work pieces with diameter over 100mm should be as follows: for water quenching 3-4 min, and for oil quenching 15-25 min, to ensure the temperature of core cools down to around the Ms point (about 300°C). According to GB699-88, the hardness of carbon steel (of 35 steel, 45 steel or 50 steel and with diameter generally not more than 200mm) after quenching and tempering can reach HB240-280[2], and the hardness after annealing generally stays below HB197 (with blank dimension of 25mm). But the hardness of the core of shaft is only HB192. Although differences exist in sizes, the hardness after quenching and tempering is much lower than the hardness after annealing. This is absolutely abnormal. To identify the structure of the shaft, take sample from the core 10mm-20mm from the surface and determine the core microstructure by using scanning electron microscope, as is shown is figure 3. It can be concluded from figure 3 that the microstructure for the core of shaft is pearlite+ ferrite, of which the ferrite is distributed in network structure as shown in figure 3(a) due to low cooling speed and short cooling period during the quenching and tempering process after forging, causing proeutectoid ferrite separates out along the grain boundary and form network structure ferrite and eventually leading to low hardness of the core.
4.2 Surface structure

The metallographic structure of the surface and around the cracks is shown in figure 4. We can see that the metallographic structure around the cracks has no obvious oxide layer and decarburized layer, which means that the cracks do not occur during the processes of casting, forging and quenching and tempering after forging, but during the surface quenching as well as later manufacturing processes.

It can also be concluded from figure 4 that the lath and acicular martensite exist in the quenched layer on surface [3], which may be caused by insufficient low temperature tempering after surface quenching. It also produces a relatively high hardness of surface – HRC54.8.

It can be concluded from figure 4(a) that obscure and black network structure exists in the quench hardened layer on surface, which is the low carbon martensite formed by network ferrite structure that goes through quenching and tempering during surface quenching. Low carbon martensite itself is prone to produce self-tempering phenomenon, and therefore make the sample susceptible to corrosion. High carbon martensite is formed by pearlite structure that goes through quenching and tempering, which is of large specific volume and is prone to generate volume expansion, thus make the surface layer produce radial tensile stress. This is the root cause for the peeling and cracking on the shaft [4].

Figure 5 is the subsurface structure under the quench hardened layer. It can be concluded that the subsurface structure is basically the same as core structure (observation can be conducted through comparison between figure 3 and figure 5).

Because the structure in subsurface is network structure ferrite [5], and the surface structure is the quenched high carbon martensite structure, coefficient of linear expansion of subsurface and surface structure is different, large tensile stress will produce in cooling and contraction, which is one of the reasons for the peeling and cracking of the metal on the surface.
5. Conclusions
Reasons for the peeling and cracking on the surface of the shaft manufactured of 45 steel with a diameter of 130mm are as follows: the low cooling speed and short cooling period during the quenching and cooling process after forging leads to generation of network structure ferrite (and low hardness of the core); low carbon martensite (prone to erosion) is generated from network structure ferrite during surface quenching, and the pearlite structure surrounded by network structure ferrite, of which the carbon contents is higher than that of steel, generates high carbon martensite during surface quenching. And because the high carbon martensite has large specific volume and is prone to generate volume expansion, it makes the surface layer produce high radial tensile stress. The thickness of surface layer reduces after grinding and thus the peeling and cracking is produced under the tensile stress. According to documents, the peeling and cracking belongs to one of the 4 typical quenching cracks of steel pieces. Uneven structure along the hardened layer during surface quenching is easy to produce this typical peeling and cracking on surface.

Meanwhile, it shall be pointed out that delayed tempering or insufficient tempering of the shaft after surface quenching which leads to failure to timely eliminate the quenching stress on surface (and a relative high hardness of surface– HRC54.8) may also be the reason for the peeling and cracking on surface of the shaft.

Reference
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