Carburized Layer Cracking Analysis of Counterweight Blocks of Speed Controller

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Abstract. Trace and fracture analysis, metallographic examination, residual stress testing, and material analysis were carried out, coupled with examining the failure timeline, to analyze the cracking problem of 12CrNi3A steel counterweight blocks under multi-factor coupling. The results show that the cracks of the counterweight blocks are intergranular microcracks in the carburized layer and they are delayed cracks under the joint action of microstructure stress, grinding stress and hydrogen. The delayed cracking of the counterweight blocks is mainly related to abnormal hydrogen absorption during surface treatment and poor grinding quality. The obvious microstructure segregation in raw material and the thicker carburized layer promoted the cracking. The following measures should be comprehensively taken to prevent such failure: strictly controlling raw material quality, hydrogen absorption and stress, as well as increasing the processes to remove hydrogen, reduce stress and stabilize microstructure.

Keywords. Carburized layer; Intergranular crack; Delayed cracking; Multifactor coupling; Abnormal hydrogen absorption; Grinding defects; Microstructure segregation.

1. Introduction
Carburizing is a chemical heat treatment method widely used in industry. It can produce a hard and wear-resistant layer on the workpiece surface of low carbon steels or low carbon alloy steels, used to withstand friction, wear and contact loads. Despite the long history of carburizing technology and abundant experiences in this field, cracking failure continues to occur to carburized products because the carburizing quality is affected by material composition, microstructure, processing as well as subsequent grinding, surface treatment and many other factors [1, 2]. Especially in many cases, the failure is caused by more than one factor, so the analysis of such problems becomes more complicated and failure prevention is difficult to carry out effectively.

When magnetic inspection was carried out on the counterweight blocks for speed controller in the final assembly stage, it was found that 85% of the products had cracks, and the cracks were distributed...
in the carburizing layer of the end face. In the present work, trace and fracture analysis, metallographic examination, residual stress testing, and material analysis were carried out, coupled with examining the failure timeline, to analyze the cracking problem of the counterweight blocks under multi-factor coupling.

2. Material and Analytical Methods
The counterweight blocks are made of 12CrNi3A steel. The processing procedures of the cracking end face include turning the end face, carburizing, heat treatment, grinding plane, magnetic detection, bluing treatment, magnetic detection, and grinding to remove the bluing layer. No cracks were found during magnetic detection. The cracks occurred in the storage stage of the finished products, with obvious time delay. The cracks basically propagated radially, as shown in figure 1.

Trace and fracture analysis was carried out with a LEICA DMS1000 stereomicroscope and a CAMSCAN 3100 scanning electron microscope. Metallographic examination was carried out with an OLYMPUS GX51 metallographic microscope. Hardness testing was carried out with a QNESS Q10A+ Vickers hardness tester. Residual austenite content was tested with a BRUKER D8 XRD. Hydrogen content was determined with a LECO TCH600 oxygen nitrogen hydrogen analyzer.

3. Experimental and Results

3.1. Observation of Trace and Fracture
The appearance of the end face of the counterweight blocks is shown in figure 2. The end face is densely covered with grinding processing marks, but the overall surface is relatively flat. Some scratches are thick, the cutting marks are round and blunt, and local plastic deformation can be seen. No obvious cracks are found on the surface.

Figure 2. Processing trace of the end surface of counterweight block (a) Magnified morphology (b) SEM morphology.
The cracks were artificially opened to analyze the fracture characteristics. It is found that there is an intergranular fracture zone tens of microns wide at the fracture edge, and the rest is covered with dimples. At the intergranular fracture zone, the grain surface is clear, without obvious oxidation pollution, shown in figure 3.

Figure 3. Micro morphology of the crack fracture (a) Position of intergranular zone (b) Morphology of intergranular zone.

3.2. Metallographic Examination

The end face and cross section perpendicular to the end face of a cracking block were ground and polished to observe the cracks and microstructure.

After the cracking end face was polished, a large number of microcracks can be seen under a metallographic microscope. The cracks are of different lengths and roughly distributed along the radial direction. Their propagation path is zigzag and multi-branched, as shown in figure 4.

The cross-section morphology is shown in figure 5. Multiple microcracks are found near the end face. The direction of the cracks is roughly perpendicular to the surface, and the depth ranges from tens of microns to more than one hundred microns. The cracks are small and the propagation path is zigzag. At the sub-surface zone, the cracks are locally net-like.

Figure 4. Crack morphology of end surface (polished state).

Figure 5. Crack morphology of cross section (polished state).
After etching, the microstructure of the cracking area was observed. Microstructure segregation can be seen on the surface of the end face, with alternating distribution of light and dark microstructure, which is all martensite at high magnification, and cracks can be seen, as shown in figure 6. The cross-section microstructure is shown in figure 7. A bright white burn layer can be seen on the surface of the carburized layer, and the microstructure of the carburized layer is sorbite, without network carbides. Microcracks are located in the carburized layer and propagated along the grain boundaries. Banded microstructure segregation can be seen in both the carburized layer and matrix, and the core microstructure is tempered sorbite.

![Figure 6. Microstructure of the end face and crack morphology.](image)

![Figure 7. Metallographic structure of the cross section (a) The carburized layer (b) The matrix (c) White burn layer on the surface (d) Near the crack.](image)

3.3. Hardness Testing
The hardness of different microstructure areas of a cracking block was tested, and the results are shown in table 1. The hardness of the carburized layer is near the lower limit of the technical requirements, and the hardness of the microstructure segregation zone fluctuates greatly, locally
exceeding the technical requirements.

**Table 1.** Hardness testing results of a cracking counterweight block (HV500).

| Position                      | Test result | Average value | Technical requirement |
|-------------------------------|-------------|---------------|-----------------------|
| Near surface of infiltration layer | 647 647 635 650 664 649 | 655–745 |
| Heart light tissue            | 432 436 424 430 420 428 | 273–404 |
| Dark tissue in the heart      | 357 333 370 369 377 361 |  |

The hardness gradient of the carburized layer was measured and the depth of the carburized layer was evaluated based on the microhardness of 550HV. The carburized layer depth of a cracking block is 0.91mm and that of an uncracking one is 0.96mm. Both of them are higher than the technical requirements of the carburized layer after machining (0.5mm–0.8mm). The hardness gradient of the carburized layer of the two blocks is shown in figure 8. The hardness of the two layers varies gently, and the surface hardness of the uncracking block is relatively higher.

![Figure 8](image)

**Figure 8.** The gradient change of hardness of the carburized layer.

### 3.4. Residual Stress Testing

The surface residual stress of the end face of a cracking block and an uncracking one was tested in the tangential direction (vertical to crack). The testing results are shown in table 2. It can be seen that in the tangential direction, both of the blocks have compressive stress.

**Table 2.** Testing results of tangential residual stress on the surface of carburized layers (MPa).

| Test piece       | Point 1 | Point 2 | Point 3 | Point 4 | Point 5 | Point 6 | Average value |
|------------------|---------|---------|---------|---------|---------|---------|---------------|
| 1# cracked parts | -725    | -755    | -868    | -802    | -711    | -738    | -766          |
| 1# cracked parts | -798    | -623    | -658    | -849    | -798    | -869    | -765          |

The gradient distribution of residual stress of the cracking end face was tested, and the results are shown in figure 9. The residual compressive stress on the surface of the end face reaches a maximum of -600mpa, and then steeply decreases to about 10MPa at the position 20–30μm away from the surface. Then the stress gradually increases and reaches another peak at the position about 0.9mm away from the surface. That is, the whole carburized layer has residual compressive stress. However, there is a thin layer with very severe stress gradient change near the surface, as shown in figure 10.
3.5. Hydrogen Content Testing
Samples were taken from surface layer of the cracking end face to test the hydrogen content in the material. The hydrogen content is 3ppm and 4ppm, respectively.

3.6. Residual Austenite Content Testing
The residual austenite content in the carburized layer of a cracking block and an uncracking one was tested. The residual austenite content of the two blocks is 6.23% and 13.14%, respectively.

4. Analysis and Discussion
It is observed that the cracks of the counterweight blocks are distributed evenly in the surface of the carburized layer, and the propagation depth is only about 100μm. The cracks propagated along the grain boundaries, multi-branched. The fracture surface presents intergranular fracture characteristics, and the grain surface is clean, without obvious oxidation, and the artificial fracture is dimple fracture. Therefore, the cracks of the counterweight blocks are intergranular cracks, with the common characteristics of grinding cracks and hydrogen induced cracks. Further, the cracks of the counterweight blocks are different from ordinary grinding cracks because there is obvious delay in the forming time (they occurred during the storage after all machining procedures). Hence, it can be assumed that they are delayed cracks under the joint action of the microstructure stress of the carburized layer, grinding stress and hydrogen.

The main influencing factors of such cracks include hydrogen, stress and sensitive microstructure [3, 4]. In this case, there are many factors which may promote the cracking of the blocks, such as the thicker carburized layer, sharp change of residual stress, microstructure segregation of raw material,
and surface grinding burn. Therefore, it is of great importance to distinguish the primary factors and the secondary ones.

According to the survey, the cracking counterweight blocks are made of the same batch of raw material, with the same batch of heat treatment and grinding, and after a month or so of time after grinding no crack was found during magnetic inspection, which means that material segregation, hydrogen absorption during carburizing, and grinding burn did not directly result in the cracking of the counterweight blocks, and they are not the major factors leading to the failure. From the point of time, after the counterweight blocks were blue-treated and stored for a period of time, many blocks were found to have cracks during magnetic inspection, indicating that the cracking of the blocks is related to hydrogen absorption in the process of bluing treatment. Bluing is an oxidation process, but abnormal hydrogen absorption may occur if the surface cleaning process such as oil removal by pickling is not properly handled. The hydrogen content near the end face is more than 3ppm, indicating there was abnormal hydrogen absorption during the process of bluing treatment. At the same time, the grinding marks of the end face are round and blunt, and there is surface grinding burn, indicating that the grinding tool was blunt and the wear heat led to secondary decomposition of residual austenite in the carburized layer (so the residual austenite content of the cracking block is significantly lower than that of the uncracking one), leading to the rise of local hardness and residual stress gradient and promoting the forming of cracks. Therefore, hydrogen absorption during surface treatment and abnormal grinding are the main reasons for the delayed cracking of the carburized layer.

In addition to the above factors, the influence of thicker carburized layer and material microstructure segregation on the cracking of the counterweight blocks shouldn’t be ignored.

The residual depth of the carburized layer of the counterweight blocks exceeds the upper limit of the technical requirements after processing. The thicker carburized layer means larger hydrogen absorption amount in the carburizing process, which is a negative factor [5]. The original residual stress gradient curve of the normal carburized layer is shown in figure 11. Compared with figure 9, it can be seen that after surface processing, the surface layer with mild stress gradient has been removed, and the area with steep stress gradient moves outward, which also promoted hydrogen-induced cracking.

![Figure 11. Distribution gradient curve of residual stress in carburized layer of common steels (before machining) [6].](image)

The residual stress of the carburized layer of the blocks is normally compressive stress, but microstructure segregation is obvious, and local microstructure hardness is very high, increasing the hydrogen embrittlement sensitivity. The residual austenite content of the carburized layers varies greatly. If martensite transformation occurs during grinding and subsequent process, the residual stress gradient in the surface layer may be further increased, also promoting the delayed cracking.

Overall, the failure reason of the counterweight blocks is complex, involving such aspects as
material, grinding and surface treatment. The following measures should be comprehensively taken to prevent such failure: strictly controlling raw material quality, hydrogen absorption and stress, as well as increasing the processes to remove hydrogen, reduce stress and stabilize microstructure.

5. Conclusions
(1) The cracks of the counterweight blocks are intergranular microcracks in the carburized layer and they are delayed cracks under the joint action of microstructure stress, grinding stress and hydrogen. The delayed cracking of the counterweight blocks is mainly related to abnormal hydrogen absorption during surface treatment and poor grinding quality.

(2) The obvious microstructure segregation of the raw material and the thicker carburized layer promoted the cracking.

(3) The following measures should be comprehensively taken to prevent such failure: strictly controlling the quality of raw material, hydrogen absorption and stress, as well as increasing the processes to remove hydrogen, reduce stress and stabilize microstructure.

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