Study on Flakes of a Steel Roller

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Abstract. The study of flakes is rare, but once it occurs, the material will suddenly burst, and the consequences are very serious. In this paper, the surface burst reason of a steel rolling mill backup roll was analyzed. The backup roll material meets a criterion of 86CrMoV7 ingredient, there are silver gray round and oval defects on macro fracture surface, visually there are more silver gray white fisheyes on the debris of the failure roller. Microscopic fracture morphology has obvious brittle fracture characteristics. The hydrogen of local surface area measured failure roller reaches 9×10^{-4} %, more than three times the allowable amount that flake no appear. Failure roll hairline cracks, or snow flakes assessed according to the standard are grade 2-3, which is a more serious flake level. The analysis results show that the flake is the main cause of the backup roll premature failure.

1. Introduction
The sample consigned by a stainless steel factory is a relic avalanched from the backup roll of a steel roller, shown in Figure 1. Failure roll diameter is 1020mm, weighing about 28 tons, steel trademark is 86CrMoV7, the surface hardened layer depth is require greater than 15mm. Shore hardness of hardened layer 70 ~ 75HS. The backup roll failed after service only 12 days, the incidence is a premature failure.

The fracture fragment showed in Figure 1 was salvaged from cool emulsified liquid tank, placed in the air for a month to do failure analysis evaluation. Fracture fragment (broken pieces) is only the thinnest 2 mm, referred to as the arrow A; the thickest is 21.5mm, referred to as the arrow B. A large number of fish-eyes can be detected, referred to as the arrow E.

Figure 1. Appearance of sample: (a) inspected roll; (b) roll debris.
2. Experimental
The failure roll was inspected visually and macroscopically. The defected roll was analyzed by optical microscopy and chemical analysis; for completing the characterization of the materials, the hardness and hydrogen content were measured also. The chemical analysis was carried out by WAS FOUNDARY MASTER desktop vacuum spark emission spectroscopy (Germany), the hydrogen content was tested by TCH600 Nitrogen-Oxygen-Hydrogen series of Determinator (LECO Corporation, USA). The fractured surfaces were ultrasonically cleaned and observed by a scanning electron microscope (SEM) equipped with EDX.

Metallographic observation was carried out by Leica DMI5000M. The sample was etched with 4% nitric acid alcohol solution.

3. Results and discussion

3.1. Composition and microstructure analysis
Sampling from arrow C in Figure 1 was take to conduct the component analysis according to Standard E415, the chemical composition of sample was detected by desktop vacuum spark emission spectroscopy. The test results in Table 1 indicate C and Cr are higher compared with the DIN standard components, the other components are within the scope of the standard components.

| Materials                  | Compositions (wt.%) |
|----------------------------|---------------------|
|                            | C       | Si     | Mn     | P  | S    | Cr    | Mo    | V    |
| Sample                     | 0.92    | 0.24   | 0.36   | <0.003 | <0.005 | 2.16  | 0.20  | 0.10 |
| Germany DIN standard for 86CrMoV7 | 0.83~   | 0.15~  | 0.30~  | ≤  | ≤    | 1.60~ | 0.20~ | 0.05~ |

Table 2. Hydrogen content of roll debris.

| Sample | 1   | 2   | 3   | 4   | 5   |
|--------|-----|-----|-----|-----|-----|
| Hydrogen (ppm) | 2.9 | 9.8 | 14.7| 8.7 | 8.9 |
| Average (ppm)   | 9.0 |

Figure 2. Metallographic structure of backup roll hardened layer: (a)Inspect field of more carbide; (b) Inspect field of little carbide.

Hydrogen content was measured according to the Chinese standard GB/T 223.82-2007 and reference to ISO14284 and E1447-09 [1,2,3], sampling from arrow D in the fracture of failure roll, measuring the average amount of residual hydrogen in steel is $9 \times 10^{-4}$%, the result is listed in table 2. Reference for field experience data, Cr-Mo steel no appear flake allows hydrogen content in steel is
less than $3 \times 10^{-4}\%$\[4\], the hydrogen content in steel compared with the produced empirical data, is 2 to 3 times more than the allowance.

### 3.2. Metallographic examination and hardness

Sampling at the arrow D in Figure 1 to test the microstructure and hardness, the sample thickness is 20mm, from the surface to inside, the microstructure is not very different, it is mainly tempered martensite and carbide, that is quench-tempered (QT) state, but uneven distribution of carbides, shown in Figure 2. The hardened depth meet the required thickness, hardness test from the surface inwards, at 2 mm from the surface hardness is 596HV (55.0 HRC, 74.0 HS), a distance of 10mm at the hardness of 596HV (55.0 HRC, 74.0 HS), the hardness at a distance of 18mm To 558HV (53.0 HRC, 71.0 HS), meet the requirements.

### 3.3. Macro-analysis of the fracture of the roll

There were signs of fatigue, as shown in Figure 1, the arrow C, the beach pattern features show that, from fatigue to fracture is a very short process, the fatigue fracture characteristics of the fracture surface of the total area of about 2 to 3%, 97 ~ 98% of the fracture Surface has a brittle fracture.

The steps on the fracture surface features shown in Figure 1 at arrow G indicates that there was stress after heat treatment, local internal stress is large, affect the premature failure of the roll. Residual stresses are an inescapable concomitant of manufacturing and fabrication processes and they can impact dramatically on machining operations and on structural integrity\[5\].

There were significant features of flake, referred to the arrow E in Figure 1, the silver gray flakes number is more, some reference call it as “fisheye”\[6\]. Affected areas are recognized on fracture surfaces by their brittle appearance and high reflectivity, which usually contrasts with the matte appearance of surrounding regions of ductile fracture\[7\]. The typical shape shown in Figure 3, there are basically three kinds of flakes in the fracture surface: circle flake, oval flake and the flat (cluster of dense dots), the size of circle and elliptic flake sizes, the smallest is about 1mm, the largest is about 4mm and the flat area is larger.

The flake (“snow flake”) on longitudinal section of the pieces can be observed for half ball, is a kind of obvious volume defects. In addition to the steel fracture have visual visible silver spots on the surface of outside, still have the following characteristics:

**Groove:** In the flake spot region, Visualizing with a magnifying lens, there are circles around the surface of the white spot, and the groove features can be captured by general camera, as shown arrow in Figure 4.

![Figure 3](image)

**Figure 3.** Flake morphology on the fracture surface : (a)circular defect; (b) oval defect.

**Hairline cracks:** Breaking a bar from the arrow F in Figure 1, and its size is shown in Figure 4. In the fragments of the longitudinal section, no acid etching, it can be observed that the fisheye is hemisphere-shaped, is a distinct body defect. There are white spots in the fracture surface shown by arrow E in Figure 1, grinding the cross-section surface vertical with the white point according to the
sampling requirements of Metallographic analysis, the finish is \( V7 \sim 8 \) by grinding up to water mill with 700 # paper for metallograph, then immersing and cook in solution of water to hydrochloric acid by 1:1 in the 70 ~ 80°C for 30 minutes, the “hairline cracks” pattern can be seen obviously, as shown in Figure 5. The hairline crack is a hydrogen-induced crack. Hairline cracking is important with respect to service failures, because such a crack may extend by fatigue and so initiate catastrophic fracture[5].

**Figure 4.** Fisheyes on the vertical section fracture surface.

**Figure 5.** Hairline cracks morphology (the strip broke off from figure 1 arrow F).

Flakes are short discontinuous internal cracks attributed to stresses produced by localized transformation and hydrogen solubility effects during cooling after hot working. In an etched transverse section, flakes appear as short, tight discontinuities which are usually located in the midway to center location of the section. They are also known as shatter cracks or hairline cracks. The above macro-fracture appearance has the characteristic of flake [5,8]. Failure roll hairline cracks, or flake assessed according to GB/T 1979-2001 standard is grade 2 or 3, is a flake more serious level. It’s a defect not allowed to exist.

3.4. Fractography via scanning electron microscopy (SEM)
Investigation by SEM, the micro-fracture have several morphology, flake local area showed intergranular fracture, as shown in Figure 6. Cloud shaped fracture morphology, as shown in Figure 7.(a) Corrugated fracture morphology, shown in Figure 7.(b), microporous and cleavage (flagstone-like) morphology as shown in Figure 7(c). Microporous could result in hydrogen aggregation. These fracture morphology are brittle fracture.

**Figure 6.** Intergranular fracture morphology (a) Intergranular fracture (b) Intercrystalline fracture morphology (c) Cleavage (flagstone-like) and intercrystalline fracture.
3.5. Comprehensive analysis

According to the observation and analysis above, in the macroscopic fracture surface, visual failure roller fragments have more silver round and oval flakes. Failure roll hairline cracks, according to China GB / T 1979-2001 standard assessment 2 to 3, is a more serious level of snow flake. And according to ASTM E381-01, flake is a defect not allowed to exist[9,10]. Hairline cracks in steel main characteristic snow flakes, snow flakes generally easy to focus on the ingot 2/3R (radius) region, at the surface are rare. If there was a concentration at surface of snow flake, snow flake at 2/3R region will more serious.

Flakes are internal fissures in large forgings and large cross-section of rolled steel induced by a combination of high hydrogen content and localized stresses [11,12,13] . In most cases the distribution center near rolled or forging or a certain depth from the surface. In the longitudinal fracture of steel the flakes present circular or oval-shaped silver-white spots, after polishing and etching the transverse slice their are shown as elongated hairline cracks [6]. Ren believed flake is a hydrogen induced crack [14]. This is the definition of flakes, flake is essentially steel internal hairline crack, it can be said steel interior hairline crack is flake, also known as fisheyes[6,15,16].

Steel in high temperature have a high content of dissolved hydrogen, that can not be discharged at a low temperature, aggregation in the metallic inclusions, micro-cracks at the grain boundary phase boundary or even form bubbles. The amount of hydrogen in steel, the reference data field experience steel, Cr-Mo steels do not appear in the snow flake allows the hydrogen content of not more than $3\times10^{-6}$%, fail roll surface measured hydrogen partial area reached $9\times10^{-6}$%, more than three times the allowable amount[17]. It is recognized that the best method of avoiding hydrogen flake is to reduce the hydrogen concentration in steel to typically less than 2ppm[18,19].

Woodtli found that a large number of fish eyes can be detected in the fracture surface of a tensile specimen. This type of hydrogen embrittlement is also called internal hydrogen embrittlement and is explained by the pressure theory based on thermodynamic principles. The quation for the balance between the atomic and gaseous hydrogen is:

$$C_{H} = 135 \sqrt{P_{H_{2}}} - 6500 / RT$$

Where $C_{H}$ is the hydrogen concentration in ppm and $P_{H_{2}}$ the hydrogen pressure in MPa in the solid phase of the adjacent gas phase. R is the gas constant and T is the absolute temperature. Accordingly, 1 ppm of dissolved hydrogen is balanced by gaseous hydrogen at room temperature and at a pressure of $2\times10^{5}$ MPa [6]. So, high hydrogen content will result localized stresses, hydrogen-induced cracks. A few parts per million of hydrogen dissolved in steel can cause hairline cracking and loss of tensile ductility. Even when the quantity of gas in solution is too small to reduce ductility, hydrogen-induced delayed fracture may occur. Hairline cracking usually follows prior austenite grain boundaries and seems to occur when the damaging effect of the dissolved hydrogen and austenite to martensite
transformation stress superposition[5]. So the destroyed area according to the reflection of their surface and high brittleness up from fracture identification; They often and ductile fracture area around coarse matte surface form bright contrast. This characteristic has made people habit to this area is called "flakes" or "fisheyes"[7].

Flakes are due to the joint action of excessive hydrogen content in steel and the internal stress, that is mainly to two factors: the hydrogen content in steel and the internal stress of steel during cooling after hot pressure processing. Also, the higher amount of hydrogen is only a necessary condition for generating the flakes, the internal stress generated in the steel during cooling after hot pressure processing is sufficient condition to produce flakes. Only the action of hydrogen, billets after hot pressure processing is not necessarily form flakes, only in the condition of large internal stress, the high hydrogen content of the billets will produce flakes. Snow flakes are generally not present at high temperatures[20].

If the ingot owing to high temperatures have a high content of dissolved hydrogen, can not be discharged at a low temperature, more hydrogen diffusion in microvoid- the grain boundary, phase boundary or even in the metallic inclusions of ingot core part of, while the hydrogen ions transform into molecular hydrogen, the hydrogen generated a lot of pressure in microscopic voids [5,21]. In the forging process, if forging inadequate or improper forging ratio, microvoid in ingot core part can not be welded together and continue to exist, these microscopic voids will become the core of the flakes. Especially for forging inadequate or improper forging ratio material, its internal voids smaller, resulting in the original microvoid set. Internal stress caused by the dislocation collection, lead to aggregation and redistribution of hydrogen in steel. When the partial hydrogen content reaches a certain amount, due to the hydrogen atom pinning effect hinders the movement of dislocations, undermines the plasticity of steel, the steel become brittle. The steel loss of ductility is easy to produce the steel local brittle cracking in hydrogen hangout (loosen unwrought binding sites) along the direction of the metal strength weak under the same effect of hydrogen pressure and internal stress, which form the so-called hydrogen induced cracking-flakes[22].

4. Conclusion
The surface burst reasons of a steel rolling mill support roller were analyzed. The support roll material meets 86CrMoV7 steel. The failure roll surface local hydrogen content was up to $9 \times 10^{-4}$ %, more than three times of the hydrogen content for Cr-Mo steel to ensure there are no “fisheyes” or flakes. Silver circular and elliptical defects spread over the macroscopic fracture surface, visually there are more “fisheyes” on the silver failure roll debris. Failure roll hairline cracks, or flake assessed according to Chinese GB/T 1979-2001 standard is grade 2 or 3, is a flake more serious level. The cracking satisfies the formation conditions and has morphology characteristics of flake. Flakes cause the supporting rollers premature failure. It is recommended that take necessary heat preservation measures to dehydrogen of billet in the forging cooling process.

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