Prevention of Sharp Fracture Caused by Large Size Inclusion in Cold Heading Steel

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Abstract. The cracking of cold heading steel during drawing was researched in this paper. The defects were detected by scanning electron microscope and EDS energy spectrum analysis, the direct causes of cracking were discussed and analysed, and the corresponding improvement measures were put forward. Results showed that the large size inclusions with high alumina content in steel were the main cause of cracks in cold heading steel due to their poor deformation ability. The plasticity of inclusions could be controlled through optimization of refining slag to reduce both the CaO and Al₂O₃ content.

1. Introduction

Cold heading steel as the material for bolts, nuts, studs, rivets and other fasteners, is widely applied in machinery manufacturing, engineering construction, vehicles, home appliances and other fields. The main production process of the hot rolled wire rod is as follows, pickling phosphating station, experience drawing, cold heading molding, wire rubbing, quenching and tempering treatment, galvanizing and packaging.

In the process of cold drawing, the nib fracture is usually exposed in the core. On the one hand, the internal defects of raw materials such as inclusion at the core of steel wire, looseness, shrinkage, reticular carbide and other segregation [1, 2] are the factors that can cause the crack source in the center [3]. On the other hand, external factors such as high rotation speed set in the drawing process, large compression rate in some passes and working cone angle [4] are also the possible impact factors. The cold heading steel must have good performance in plasticity, dimensional accuracy and internal quality, to be adapted to the large deformation and fast processing speed during machining, that also put forward higher requirements for the melting and rolling processes.

In this paper, the cracking of cold heading steel during drawing was researched. The defect samples were detected, the direct causes of cracking were discussed and analyzed, and the corresponding improvement measures were put forward.
2. Fracture morphology and analysis
The chemical composition of cold heading steel is shown in Table 1. This steel is silicon deoxidized, with high percentage of silicon and low acid soluble aluminum content, and serious breakage occurred during drawing of the wire rod from φ6.5mm to φ4mm, after pickling and phosphatization. LEICA DVM6 3D stereography microscope was used to observe the macro morphology of the 4mm drawn fracture. EVO18 Zeiss scanning electron microscope and EDS energy spectrum analysis were used to examine and analyze the crack source.

| Element | C  | Si | Mn | P  | S   | Als | Cr | Ni |
|---------|----|----|----|----|-----|-----|----|----|
| Percentage | 0.46 | 0.19 | 0.72 | 0.01 | 0.002 | 0.002 | 0.026 | 0.011 |

2.1. The fracture morphology
The fracture morphology is shown in Figure 1. It is in the shape of dual structures, "one tip and one nest". Among the 6 steel wire fractures, three of them are (numbered 1#~3#) shown in funnel-shaped morphology, and others are (numbered 4#~6#) shown in nib shaped morphology. Nib fracture and funnel-shaped fracture belong to the same couple. The crack source of fracture is located in the central of the material, and the crack extends outward from the central region and finally leads to fracture. It is speculated that the drawing fracture of steel wire is related to the defects in the core of the steel wire.

Figure 1. Funnel-shaped fracture morphology of nib (30×)

The fractures were analyzed to confirm the main reasons. The longitudinal specimens were observed through the metallographic microscope initially, before and after corrosion, separately, as shown in figure 2. Large size of inclusions, in the radial size of 112.5μm, with round and shear plane, were discovered at the source of cracks. From the observation of the corrosion microstructure, it can be found that the matrix structure is uniform ferrite and pearlite, stretching along the rolling direction, and the inclusion separated from the matrix, didn’t extend along the rolling direction because of the limited deformation ability, resulting in crack initiation.

Figure 2 Microstructure of crack source at funnel-shaped fracture (non-corroded and corroded, 200×)

Further observation under scanning electron microscope showed that the inclusions at the three funnel-shaped crack sources were in a broken state, spherical in shape as a whole, and their radial dimensions ranged from 93μm to 140μm, as shown in Figure 3. The specific morphology of the nib fractures was shown in Figure 4. Two of the nib fractures were scratched and damaged, and the original morphology of the crack source could not be observed. In the last fracture, there were large

Figure 3. Nib fracture morphology (non-corroded and corroded, 500×)
massive inclusions at the crack source with a radial size of 116μm. It was speculated that the liquid spherical inclusions formed at high temperature were still remained in solidificated steel, and then crushed under high pressure during rolling or subsequent machining, that lead to the crack initiation. It was also concluded that the large size inclusions in the core of rod were the cause of drawing cracking.

Figure 3 SEM morphology of crack source of funnel-shaped fracture

Figure 4 SEM morphology of crack source of nib fracture

2.2. Energy spectrum analysis of large size inclusions
EDS analysis results of large-sized inclusions at the nib and funnel-shaped crack source were shown in Figure 5. They are similar in composition, mainly calcium aluminum silicate (CaO-Al₂O₃-SiO₂) inclusions, containing a small amount of Mg and S.

Their normalized mass fractions were shown in Table 2, with high Al₂O₃ content of 60.69% and 55.84%, and CaO/Al₂O₃ ratio of 0.58, 0.61, respectively, the mole fraction ratio was nearly 1, and the SiO₂ contents in the inclusions were 3.86 and 9.91%, respectively.

| No. | CaO  | Al₂O₃ | SiO₂  |
|-----|------|-------|-------|
| 3#  | 35.46| 60.69 | 3.86  |
| 6#  | 34.26| 55.84 | 9.91  |
3. Analysis and discussion

3.1. Characteristics of inclusions

The major components of large-size inclusions were projected into the CaO-Al2O3-SiO2 terpolymer phase diagram at 1873K, and the results were shown in Figure 6. They were distributed in the liquid phase region. Some scholars [5-8] have studied that the liquid inclusions in molten steel are more difficult to remove than the solid inclusions. According to the research data of Cramb A W et al. [9], the contact angle between liquid inclusions and liquid steel is less than degree of 90° (in which, at 1600℃, the contact angle of the inclusion with wt CaO/Al2O3 of 36:64 is 65°). The liquid inclusions have good wettability with liquid steel and not easy to be removed from liquid steel, and with the SiO2 content increasing, the value of contact angle is reduced, that is, it has better wettability with the liquid steel, and remains in the liquid steel more stably.

However, it was noted that the Al2O3 content in the inclusion was very high, so even it was distributed in the liquid phase region, it had relatively high melting point and poor deformation ability, which was to become the crack source, and seriously affect the processing and service performance of steel.

![Figure 6 Distribution of large size inclusions in ternary phase diagram at 1873K](image)

3.2. Source and formation mechanism of high Al2O3 inclusions in Si deoxidized steel

The original process of cold heading steel was to add ferric silicon deoxidizing agent, carbon powder, alloy, and lime during the tapping of BOF, and then a large amount of lime and calcium aluminum slag (with the composition of CaO 50wt%, Al2O340wt%) were added in the early stage of LF refining to adjust the slag fluidity, and a few amount of silicon carbide was added to control the slag oxygenability. The composition of LF refining slag was detected and shown in Table 3. It was obvious that the content of CaO and Al2O3 was high, with the alkalinity of about 2.89, and the C/A of 4.32. The Als content in the steel was about 20ppm. On the one hand, Als was derived from the introduction of residual elements in the alloy, and on the other hand, it was related to the high Al2O3 content and low SiO2 content in the slag. When the Al2O3 content in the top slag increased, its activity increased, which promoted the reduction reaction between Si in the steel and Al2O3 in the slag, thus leading to the increase of Als content in the steel and the indirect increase of Al2O3 content in the inclusions.

Through the study of inclusion involution in the whole steelmaking process, it was found that at the initial stage of refining after deoxidation, the inclusions in steel were mainly MnO-Al2O3-SiO2. With the progress of refining, the content of CaO in the inclusions increased, due to the steel slag reaction and the interaction between molten steel and refractory, which was unfavorable to the control of inclusions.

### Table 3 Chemical composition of slag (weight percentage%)

| Component | Weight Percentage |
|-----------|------------------|
| CaO       | 57.22            |
| SiO2      | 19.80            |
| Al2O3     | 13.23            |
| MgO       | 7.04             |
| TFe       | 1.06             |
| MnO       | 0.20             |
3.3. Analysis of improvement measures

In order to reduce the drawing fracture caused by large size inclusions, it is necessary to improve the purity of the material for one thing, and control the inclusions to be plastic for another. In order to improve the purity of molten steel, a few amount of aluminum could be added to take part in the deoxidation reaction to promote the formation and flotation of solid inclusions. In addition, the suitable top slag composition needed to be designed to promote the plasticity control of inclusions during LF refining process, and the low basicity slag was used to replace the calcium aluminum slag, to control the CaO content in the refining slag reduced to be less than 50% and the Al₂O₃ content less than 10%. The optimized composition of refining slag was shown in Table 4, and the drawing fracture caused by large size inclusions was effectively alleviated.

Table 4 Chemical composition of optimized slag (weight percentage%)

|     | CaO  | SiO₂ | Al₂O₃ | MgO | TFe | MnO |
|-----|------|------|-------|-----|-----|-----|
|     | 48.05| 34.02| 7.81  | 7.21| 1.24| 0.22|

4. Conclusion

(1) The large size inclusions with high alumina content in steel were the main cause of cracks in cold heading steel due to their poor deformation ability.

(2) The high alkali and Al₂O₃ content in the slag are the main reasons for the increase of Al₂O₃ content in the inclusions.

(3) In the actual production process, the design of refining slag should be further optimized to control the plasticity of inclusions and improve the workability of products.

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