Experimental Study of Strain Clamps Crimped Under Unbalanced Condition

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Abstract. In order to clarify the relationship between the efficacy loss of strain clamp joints and the crimping quality, three groups of clamp joints, crimped under unbalanced conditions at both ends, naming NY-240/40, NY-400/35 and NY-630/45 were selected and then subjected to tensile tests and X-ray inspection. After a detailed analysis of the experimental results, it can be seen that under the condition of unbalanced crimping quality, the efficacy loss all occurred on the side with better crimping quality, which provides an instructive reference for the crimping technique of strain clamps in actual project construction.

1. Introduction

Made of steel anchor and aluminum sleeve, generally connecting with aluminum wire under hydraulic compression, strain clamps are widely used in the high-voltage cable connection structure of power transmission projects in China. Used for power transmission, the aluminum wire is made of aluminum and steel, which are coaxially layered and twisted. It is called steel-core aluminum stranded wire [1]. The outer layer of the aluminum wire is wrapped by hard aluminum stranded wire with high conductivity, which is used to transmit current. The central part of the wire is made of steel with high mechanical strength so as to withstand tensile forces, as shown in Figure 1 (a). A complete crimping joint shall be formed when the strain clamp is crimped with the wire. As shown in Figure 1 (b), the steel core of the wire is crimped with the steel anchor, the wire with the aluminum sleeve, and the steel anchor with the aluminum sleeve. A small part of the tensile forces of the wire is borne by the crimping tube and the aluminum wire, and most of it is borne by the steel core connector.

\begin{figure}[h]
  \centering
  \includegraphics[width=0.8\textwidth]{figure1.png}
  \caption{Strain clamp structure.}
\end{figure}

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Problems caused by unqualified joint crimping have a great impact on project construction. Therefore, Chinese scholars have done a lot of related research on the mechanical properties of clamp crimping and the causes of the efficacy loss. Through the mechanical simulation analysis of the clamp by using Calculix, Li [2] et al. established models with different groove depths on the basis of the standard model, and discussed the influence caused by the defects of the steel anchor on the performance of strain clamp. Via macroscopic examination, electron microscope scanning, energy spectrum analysis and metallographic examination, Jing [3] et al. conducted an efficacy loss analysis on the fracture of the aluminum tube, corresponding preventive measures were also proposed. Using X-ray non-destructive testing technology, Yang [4] et al. conducted an induction analysis on the clamps. They studied the types and frequency of clamp defects, and found that at the groove of the steel anchor, under-voltage defects of the aluminum tube accounted for more. After a series of analysis on the strain clamps with different defects, Cheng [5] et al. discussed the comprehensive breaking force and weak links of the strain clamps under different conditions, and analyzed the crimping quality of the strain clamps based on the results of X-ray examination. For the internal defects of high-voltage transmission wires, Han [6] et al. proposed an X-ray visual inspection method. Under laboratory conditions, they respectively simulated and tested different internal defects such as broken steel core strands, scratches on the surface of the steel core, wires being mixed together, loose strands and insufficient crimp depth, and then they compared them with defect-less transmission wires so as to obtain the X-ray digital images of the internal defects of the wire. Wu [7] et al. analyzed and studied the pressure contact technique for strain clamps used for conductors with large-cross section. With X-ray digital imaging, Lu [8] et al. detected the actual crimped size of the steel core and aluminum sleeve of the strain clamp. In order to determine the critical point that can meet the wire tension value stipulated by the regulations, they also set up multiple sets of experiments. The cause of fracture was analyzed by Li [9] et al. after a series of examination, including analyzing the grain image orientation via EBSD, observing the fracture morphology by scanning electron microscope (SEM), tensile and hardness tests under room temperature conditions.

In practical applications, the crimping quality of strain clamps at both ends of the same steel-core aluminum stranded wire may be different, thus affecting the quality of the project. Thus, the influence of crimping quality on the performance of strain clamp when there are differences in crimping process at both ends were explored. The crimping and tensile tests have been respectively carried out on three groups of clamp joints, NY-240/40, NY-400/35, NY-630/45. Besides, X-ray inspections have been carried out on each group of clamps so as to analyze the stress condition of the strain clamps and possible causes of efficacy loss under unbalanced crimping condition.

2. Experimental Design

Strain clamp joints NY-240/40, NY-400/35, NY-630/45 have been selected as the research target, and size and modeling of the steel-core aluminum stranded wire are based on "Round Wire Concentric Lay Overhead Electrical Stranded Conductors" [10]. According to "Test Method for Electric Power Fittings: Mechanical Tests" [11], the experiments have been carried out under the standard crimping pressure of 80MPa. In consideration of the unbalanced crimping condition, different crimping pressure has been respectively applied to both ends of the strain clamps. In addition, as shown in Table 1, in order to analyze the influence of low crimping pressure on experimental results, the following crimping schemes are designed. Three groups of clamp joints including NY-240/40, NY-400/35, NY-630/45 were prepared, and five samples of each group were tested. The crimping dies and tensile testing machine are shown in Figure 2.

| Scheme No. | 1     | 2     | 3     | 4     | 5     |
|------------|-------|-------|-------|-------|-------|
| Crimping pressure at both ends (MPa) | 80-60 | 80-50 | 80-40 | 60-60 | 40-40 |
After the samples were crimped in line with the standard specification of "Mechanical Tests" [11], the edge distance of the crimping point were measured so as to preliminarily determine the crimping quality and conduct tensile tests. To test the crimping condition and monitor the change of samples after tensile test, X-ray scanning was carried out before and after the tensile test.

3. Analysis and Discussion

Assuming that the mechanical model of the steel-core aluminum stranded wire meets the basic premise of material mechanics, the steel-core aluminum stranded wire model had been analyzed in sections. As shown in Figure 3, $F_0$ represents the tensile force of the experiment; $F_1,F_1'$ the mutual clamping force between the steel anchor and the aluminum sleeve at the crimping point $\odot$ after crimping; $F_2,F_2'$ the mutual clamping force between the steel anchor and the steel core at the crimping point $\odot$ ; $F_3,F_3'$ the mutual clamping force between aluminum sleeve and aluminum wire at crimping point $\odot$ ; $F_4,F_4'$ the mutual clamping force between aluminum wire and steel core at crimping point $\odot$ ; $F_5,F_5'$ the mutual clamping force between aluminum wire and steel core at the crimping point $\odot$; $F_6,F_6'$ the mutual clamping force between the connecting pipe and the aluminum wire at the crimping point $\odot$ ; $F_7,F_7'$ the tensile forces borne by the steel core at the left and right ends at point $\odot$.

When there is no loosening at each crimping point, the mechanical model of strain clamps during tensile tests meets the specification mechanical model in Fig. 3, therefore the following equation can be listed:

Steel core:

$$F_2+F_4=F_3+F_7$$

Steel anchor:
\[ F_0 = F_1 + F_2 \]  
\[ F_1 = F_3 \]  
\[ F_3 + F_4 = F_5 + F_6 \]  

Aluminum sleeve:

\[ F_1 = F_3 \]  

Aluminum wire:

\[ F_0 = F_5 + F_7 \]  

It can be found from the analysis that the directions of the forces of \( F_4 \) and \( F_5 \)' and \( F_5 \) and \( F_6 \) are uncertain. That is to say, the positive and negative values of \( F_4 \) and \( F_5 \) in formula (2) and formula (4) will be determined by conditions on the ground, while the other forces are all tensile forces and are positive values. Besides, if the steel-core aluminum stranded wire is regarded as a whole, the following equation can be listed:

\[ F_0 = F_5 + F_7 \]  

Measurement results of edge distance of crimped samples are shown in Table 2. Crimping points \( \circ \), \( \triangle \) and \( \times \) are respectively shown in Figure 3. \( d_{\text{avg}} \) refers the average value of the measurement results of edge distance of the crimped parts, \( \sigma \) the standard deviation of the sample estimation of the corresponding recorded edge distance data, and \( d_{\text{max}} \) the allowable maximum value of the edge distance for judging whether the crimping quality is up to standard. Indicating the unqualified crimping parts, the measurements shown in bold are greater than the allowable maximum value. The estimated standard deviation \( \sigma \) of some samples (\( \sigma \) shown in bold in Table 2) is relatively greater, indicating that there is a large fluctuation in edge distance at corresponding crimped parts. Through the observation and analysis of the results, we can conclude that insufficient crimping pressure resulted in uneven crimping quality.

Table 2. Measurements of edge distance of the crimped samples (Unit: mm).

| Crimping Pressure (MPa) | 80 | 60 | 50 | 40 | \( d_{\text{max}} \) |
|-------------------------|----|----|----|----|-----------------|
| NY-240/40               |    |    |    |    |                 |
| \( \circ \)             | 30.91 | 31.11 | 30.85 | 31.01 | 31.16 |
| \( \sigma \)            | 0.132 | 0.116 | 0.0660 | 0.156 |       |
| \( d_{\text{avg}} \)    | 13.82 | 13.81 | 13.80 | 14.44 | 13.96 |
| \( \sigma \)            | 0.119 | 0.0660 | 0.0825 | 0.263 |       |
| \( d_{\text{avg}} \)    | 30.87 | 31.00 | 30.84 | 30.83 | 31.16 |
| \( \sigma \)            | 0.0989 | 0.122 | 0.101 | 0.0976 |       |

| NY-400/35               |    |    |    |    |                 |
| \( \circ \)             | 38.76 | 38.65 | 39.72 | 40.29 | 38.90 |
| \( \sigma \)            | 0.0961 | 0.616 | 0.604 | 0.464 |       |
| \( d_{\text{avg}} \)    | 13.79 | 13.80 | 13.80 | 14.49 | 13.96 |
| \( \sigma \)            | 0.111 | 0.158 | 0.109 | 0.370 |       |
| \( d_{\text{avg}} \)    | 38.82 | 38.64 | 38.63 | 38.83 | 38.90 |
| \( \sigma \)            | 0.147 | 0.130 | 0.113 | 0.254 |       |

| NY-630/45               |    |    |    |    |                 |
| \( \circ \)             | 51.40 | 51.64 | 51.35 | 54.34 | 51.80 |
| \( \sigma \)            | 0.288 | 0.194 | 0.237 | 1.30  |       |
| \( d_{\text{avg}} \)    | 15.56 | 15.49 | 15.52 | 15.82 | 15.68 |
| \( \sigma \)            | 0.196 | 0.111 | 0.202 | 0.295 |       |
| \( d_{\text{avg}} \)    | 51.40 | 51.39 | 51.38 | 51.46 | 51.80 |
| \( \sigma \)            | 0.221 | 0.296 | 0.267 | 0.162 |       |

Based on the criterion of qualified edge distance in "Test Method for Electric Power Fittings: Mechanical Tests" [11], the results show that the measurements of edge distance are up to standard
under crimping pressure of 80MPa and 60MPa; only the measurements of edge distance of NY-400/35 samples at the crimping points ① failed to meet the standard under the crimping pressure of 50MPa; Furthermore, the measurements of edge distance of samples from three groups at the crimping points ① are still up to standard under crimping pressure of 40MPa, so are the NY-240/40 samples at the crimping points ①.

It is thus clear that, testing the crimping quality only by the edge distance of the crimped samples leads to large errors. Moreover, as we can see from the results in Table 2, when crimping points ①, ② and ③ are at low pressure, poor crimping occurred firstly at point ② among relatively smaller-sized samples of NY-240/40. Among clamp samples of NY-400/35 and NY-630/45, the earliest poor crimping occurred at crimping point ① and then followed by a second one at crimping point ③, while under the crimping pressure from 80MPa to 40MPa, no poor crimping occurred at crimping point ③.

As displayed in Table 2, under crimping pressure of 80MPa, the standard deviation $\sigma$ of measurements of the edge distance is relatively smaller and the deformation of the crimped metal is also relatively well-distributed and sufficient. With the decrease of pressure, the standard deviation $\sigma$ of each part becomes bigger, the metal is therefore not fully deformed.

The tensile test results of the crimped sample are shown in Table 3. To cut down on experimental costs, slight adjustments were implemented in the initial experimental scheme. From the X-ray scanning diagram of failed samples (Figure 4), we can see that when the size of the samples is small, they can also pass the tensile tests under low pressure. For samples of NY-400/35 and NY-630/45, the efficacy loss occurred on the side with higher crimping pressure. The efficacy loss of NY-400/35 samples occurred as steel core fracture at the crimping point ①, while the efficacy loss of NY-630/45 samples occurred as broken aluminum wire at the crimping point ①.

The same test was carried out on the samples with balanced crimping pressure at both ends, and samples in three sizes all passed the tensile test under the pressure of 60mpa-60mpa. The results show that unbalanced crimping affected the test results of strain clamp. No efficacy loss occurred on samples of NY-240/40 because of their small size, and the peak tension in the tensile testing specification is 79mpa.

Under the balanced crimping pressure of 60MPa, samples of three groups shown no efficacy loss during tensile tests. For samples of NY-400/35, under the balanced crimping pressure of 50MPa, the peak pulling force required to elongate the sample to breaking point is 98.77KN, which is higher than 96.64KN under crimping pressure of 80-60MPa and 93.88KN under crimping pressure of 80-50MPa. Hence it is known that unbalanced crimping has a great influence on the stress state of the strain clamp samples.

| Crimping pressure at both ends (MPa) | NY-240/40 | NY-400/35 | NY-630/45 |
|------------------------------------|-----------|-----------|-----------|
| 80-60                              | Passed    | Steel core broke at point ① at the side with pressure of 80MPa, the peak pulling force is 96.64KN | Aluminum fracture at point ① at the side with pressure of 80MPa, the peak pulling force is 138.85KN |
| 80-50                              | Passed    | Steel core broke at point ① at the side with pressure of 80MPa, the peak pulling force is 93.88KN | - |
| 80-40                              | Passed    | -         | -         |
| 60-40                              | -         | Steel core broke at point ① at the side with pressure of 60MPa, the peak pulling force is 97.98KN | - |
| 60-60                              | Passed    | Passed    | Passed    |
| 50-50                              | Passed    | Steel core broke at point ①, the peak pulling force is 98.77KN | Failed, the peak pulling force is 87.79KN |

Table 3. Tensile test results of the samples.
According to the previous mechanical analysis, for the case of unbalanced crimping, the crimping point ④ of the connecting pipe shall be carried out according to the standard, so the pulling force of the both ends towards the steel-core aluminum stranded wire remains the same. When the clamp bears the pulling force $F_0$ during a tensile test, the steel anchor is balanced by $F_1$ and $F_2$ provided by aluminum sleeve and steel core.

When the crimping quality at point ① is good, force $F_1$ shared by the aluminum sleeve is larger, which plays a good auxiliary role for the steel-core aluminum stranded wire. The crimping of point ② mainly plays the role of conducting the force between the steel anchor and steel core, the force of $F_2$ and $F_2'$ will not be affected as long as there is no loosening. Therefore, the value of $F_2$ depends on $F_1$. Similarly, for the stress state of aluminum sleeve during stretching, the value of $F_3$ depends on the value of $F_1$.

4. Conclusion

As above, three groups of wire clamp joints including NY-240/40, NY-400/35 and NY-630/45 were subjected to crimping tests, tensile tests, and X-ray inspection. After a detailed analysis of the results, the following conclusions are obtained:

(1) Crimped under unbalanced conditions, all strain clamp samples of NY-240/40 have passed the tensile test; the efficacy loss of NY-400/35 occurred on the side with better crimping quality, and the steel core under the steel anchor is pulled off; the efficacy loss of NY-630/45 occurred on the side with better crimping quality, and the aluminum wire in the connecting pipe is pulled off.

(2) Under the balanced crimping pressure of 60MPa, samples of three groups shown no efficacy loss during tensile tests. For samples of NY-400/35, under the balanced crimping pressure of 50MPa, the peak pulling force required to elongate the sample to breaking point is 98.77KN, which is higher than 96.64KN under crimping pressure of 80-60MPa and 93.88KN under crimping pressure of 80-50MPa. Hence it is known that unbalanced crimping has a great influence on the stress state of the strain clamp samples.

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