Performance analysis and material selection of stainless steel expansion joints for power grid equipment

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Abstract. Stainless steel expansion joint, as the connecting part of GIS equipment, has the function of compensating the deformation of GIS caused by cold and hot stress. And it should at least meet the requirements of anti-corrosion and non-magnetic according to the working environment. This work investigate the performance of 304, 316L and 825 austenitic stainless steel expansion joints by metallographic analysis, hardness test, XRD analysis and magnetic analysis, and suggestions on material selection of expansion joint for power grid equipment are put forward.

1. Introduction
As an important part of the power industry, high-voltage electrical appliances are developing in the direction of compact structure, small land occupation, easy maintenance and high operation reliability, which is the inevitable trend of high quality development of the power industry. Gas-insulated switchgear (GIS) is a metal-enclosed switchgear used in the high-voltage environment, and it is filled with a certain percentage of sulfur hexafluoride or other special gases as an insulating medium [1]. GIS is composed of several high-voltage components such as busbars, bushings, circuit breakers, isolating switches, grounding switches, current transformers and voltage transformers, etc [2]. Among them diverse materials combinations has different expansion coefficients, which bring about different thermal stresses when the temperature changes. And the inconsistent expansion and contraction of various components maybe damage the components and thereby reduce the power supply reliability of the GIS [3]. Therefore, it is necessary to install expansion joints on the busbar configuration of the GIS to minimize the amount of expansion and contraction caused by the thermal stress.

The corrugated expansion joint is a flexible structure [4,5], as the connecting part of two adjacent GIS equipment shells, used for compensating the deformation of GIS including installation and adjustment, relative motion compensation between foundations, compensation displacement caused by thermal expansion and contraction, absorption of vibration during operation and so on. The corrugated expansion joint is generally composed of flange, bellows, tie rods, nut and ear plate [6], and the schematic diagram is shown in Figure 1. Thereinto, the bellows are thin-walled cylindrical components, determining the performance of the expansion joint. Since the surface of bellows expansion joints is generally not covered and exposed for a long time, most of the bellows expansion joints are made of stainless steel [7], and 304 stainless steel is used in most practical applications.
There are two major problems in the service process of 304 stainless steel [8]. One is that due to the large deformation of at the peaks and valleys of corrugated pipe during the forming processes, stress-induced martensite transformation in 304 austenitic stainless steel produces magnetism [9]. Second, due to the work hardening effect and the transformation of the structure, the residual stress of the bellows is relatively large, which increases the risk of ageing fracture and stress corrosion cracking.

2. Experimental methods

Three types of 304, 316L and 825 austenitic stainless steel bellows materials are selected, and the related properties under four conditions of undeformed, 8.65%, 14.64% and 18.47% cold working rate are studied respectively.

The metallographic structure was observed with Axio OBERVER ALM optical microscope. And the undeformed part and the place with the largest peak deformation of 304, 316L and 825 bellows parts of austenitic stainless steel were sampled respectively, then sample preparation by hot mounting. Vickers hardness tester (model MH-6) was used to detect the hardness of the deformed part in the wave crest and valley area of the bellows and the undeformed part at the end of the bellows. The test load was 100 gf and the loading time was 5 seconds.

The content of austenite transformed into martensite of stainless steel after plastic deformation was analyzed by XRD. The surface of five kinds of stainless steel samples were tested by XRD, and the results were analyzed by jade 6.

The induction of martensite in austenitic stainless steel during cold working tension was investigated by static magnetic measurement, and the Fischer-FMP30 was used to measure the deformation content of austenitic steel. The deformed part of the sample is cut by wire cutting machine, with the size of 18 mm in outer diameter, 12 mm in inner diameter and about 0.5-0.8 mm in thickness.

3. Results and Discussion

3.1 Metallographic analysis

The metallographic picture of 304 stainless steel with 8.65%, 14.64% and 18.47% deformation are showed in Figure 2 respectively. It can be seen from Figure 2(a) that the shape of small austenite crystals in the undeformed stainless steel microstructure is polygonal, and the grain boundary is clear, and there are occasionally twins in the crystals. After a small amount of deformation, the grain of 304 stainless steel is refined and a very small amount of martensite begins to produce at this point, as
shown in Figure 2(b). With the deformation increasing to 18.47%, the number of twin in austenite grains and the content of martensite increased distinctly, as shown in Figure 2(d).

Figure 2. Metallographic pictures of 304 stainless steel  
(a) Undeformed (b) 8.65% (c) 14.64% (d) 18.47%.

Figure 3. Metallographic pictures of 316L stainless steel  
(a) Undeformed (b) 8.65% (c) 14.64% (d) 18.47%

The metallographic picture of 316L stainless steel with undeformed and cold working deformation of 8.65%, 14.64% and 18.47% are presented in Figure 3 respectively. It can be found that the original stainless steel has large grains and obvious grain boundaries, showing typical austenite structure from Figure 3 (a). After cold working deformation, the austenite grains are gradually refined, and the grain size is slightly reduced, but the overall change is not obvious, as shown in Figure 3 (b,c,d).
Figure 4. Metallographic pictures of 825 stainless steel
(a) Undeformed (b) 8.65% (c) 14.64% (d) 18.47%.

The metallographic pictures of 825 stainless steel with 8.65%, 14.64% and 18.47% deformation are demonstrated in Figure 4. It can be seen from Figure 4 (a) that the grain size of flat stainless steel sample is larger and there are a few twins. After cold working deformation, the number of twins slightly increases, the austenite grain slightly refines and the grain size decreases with a variation trend not obvious, as shown in Figure 4 (b,c,d). In addition, there is no obvious martensite structure, which can be inferred that the phenomenon of microstructure transformation in 825 stainless steel almost no emerge when the strain is less than 20%.

3.2 Hardness analysis
The vickers hardness values of 304, 316L and 825 stainless steels under undeformed and cold working strains of 8.65%, 14.64% and 18.47% are shown in Table 1. The vickers hardness values of 304, 316L and 825 stainless steels increase constantly caused by work hardening. That is the grains slip and the dislocations tangle, which makes the grains elongate, break and fibrosis, and the residual stress occurs in the metal, during the plastic deformation of metal [10].

Table 1. The vickers hardness of 304, 316L and 825 stainless steel (hardness /HV).

| Materials | Thickness/mm | Undeformed | 8.65% | 14.64% | 18.47% |
|-----------|--------------|------------|-------|--------|--------|
| 304       | 0.5          | 166.0      | 277.4 | 280.9  | 300.3  |
| 316L      | 0.5          | 149.0      | 232.0 | 261.2  | 275.5  |
| 825       | 0.6          | 163.5      | 251.3 | 256.8  | 265.6  |

According to the above vickers hardness data, the variation chart of microhardness with different cold-working rate are shown in Figure 5. It can be seen that the hardness values of three kinds of steel after cold working deformation show an upward trend, and the hardness values of stainless steel increase significantly when the tensile ratio increases from 0 to 8.25%, indicating that the hardness of stainless steel can be significantly improved by stretching. Moreover, the hardness of 825 steel changes little with the increase of cold working deformation rate after 8.25% cold working deformation.
3.3 XRD analysis

The XRD spectra of 304 stainless steel are presented in Figure 6. Among them, the γ peaks represents austenite peak (including γ (111) and γ (200), etc), and α peaks indicate martensite peak (including α' (111) and α' (211), etc). It can be seen from Figure 6 that the α' peak increased and the γ peak decreased in turn with the increase of cold working rate. Then, the increase of α' (111) and α' (211) peaks illustrate that martensite mutation occurs in a part of austenite in 304 austenitic stainless steel during cold working deformation.

The XRD spectra of 316L stainless steel are shown in Figure 7. There are typical austenite phases in undeformed 316L stainless steel, mainly composed of austenite γ (111), γ (200), γ (220) and γ (331) peaks, and there is martensite peak α' (111) exist which may be produced in the process of cold working. Along with the increase of cold working rate, the γ peak strength of austenite gradually decreases and the peak γ (111) intensity decreased significantly, meanwhile the α' peak intensity increased gradually. This indicates that the transformation from austenite to martensite occurs in the internal structure of 316L stainless steel during the change of cold working process.

It can be seen from Figure 8 that there are no martensite peak in the XRD spectra of 825 stainless steel under different cold working rate. And there is no obvious change of austenite peak when the cold working rate is less than 15%, whereas the γ (111) peak intensity reduce observably and γ (200) peak intensity increases sharply when the cold working tensile ratio is more than 18.47%. There is no
martensite peak, which indicates that there is no obvious transformation from austenite to martensite in 825 stainless steel during cold working.

3.4 Magnetic analysis

The martensite content of 304, 316L and 825 stainless steel bellows are obtained by magnetic analysis under undeformed and cold working rate of 8.65%, 14.64%, 18.47% respectively, as shown in Table 2. It can be seen that the martensite content of 304 stainless steel bellows will increase gradually with cold working rate increases, which indicates that the austenite grain is refined and the grain size is reduced, which is consistent with the conclusion of metallography. The martensite content of 316L stainless steel does not increase significantly in the range from undeformed to 18.47% cold working deformation. And the content of martensite in 825 stainless steel is almost unchanged after tensile deformation.

| Materials | Thickness/mm | Undeformed | 8.65% | 14.64% | 18.47% |
|-----------|--------------|------------|-------|--------|--------|
| 304       | 0.5          | 0.21       | 0.37  | 0.92   | 2.23   |
| 316L      | 0.5          | 0.10       | 0.12  | 0.12   | 0.12   |
| 825       | 0.6          | 0.22       | 0.21  | 0.22   | 0.20   |

4. Conclusion

Through metallographic analysis, XRD test and magnetic analysis, it is found that 304 and 316L austenitic stainless steel are typical austenite structure under normal conditions, and a certain amount of martensite will be produced after cold working deformation. And no martensite is found in 825 austenitic stainless steel after the cold working deformation. By the vickers hardness test, the micro-hardness of each steel have been changed along with the cold working deformation increase. Among them, martensite structure appeared in 304 grain and at the grain boundary, and the martensite content and hardness increased obviously with the increase of cold working rate. When the cold working rate of 316L stainless steel is less than 20%, the martensite transformation and hardness change are unobvious. And the hardness of 825 steel is not changed significantly with cold working deformation increasing. Because the actual deformation of expansion joint bellows is usually between 10% and 15%, 316L and 825 have less martensitic transformation and lower hardness than 304 stainless steel during the cold working process, which illustrate that 316L and 825 stainless steel are recommended as the preferred materials.

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