The Application and the Problems of High Strength Steel on Penstock in Chinese Hydroelectric Station

Ming LI and Wenlin JIANG

Quality Inspection & Test Center of Hydro Steel Structure, Ministry of Water Resources, No. 110, Yinghe Road, Zhengzhou, Henan 450006 P.R. China. E-mail: gljd@sina.com

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The application of high strength steel has increasingly improved the technology on penstock manufacture and assembling, as well as management, with economy benefit being equally obtained. However, some misunderstandings on using high strength steel plate are still existed, which weaken their advantage. In this paper, the following problems are discussed.

1. Introduction

China has the richest waterpower resource in the world, which, however, is only limitedly developed. By the end of 2000, the installed capacity of 7.935×10^4 MW has been developed, which was only 21% of the whole available waterpower, accounting for 24.9% of the total power system. With the rapid development of economy and increasing requirement of environment protection, developing waterpower, which is clean and reproducible, has become one of China’s important energy policy, and year 2005 promises a installed capacity of 9.5×10^4 MW, which would be 25.1% of the whole available waterpower.

With the increasing construction of waterpower station in China, which has larger capacities and higher water heads, especially in the case of pumped storage power station, high strength steel being employed in penstocks is becoming a trend.

The application of high strength steel has largely improved the technology on penstock manufacture and assembling, as well as management, with economy benefit being equally obtained. However, some misunderstandings on using high strength steel plate still existed, which weaken their strength. In this paper, the following problems are discussed.

2. Overly Request on Welding and Nondestructive Test (NDT)

High strength steel is generally regarded as bad weldability, which causes high request on welding technology and NDT test. As a matter of fact, the new type of high strength steel has excellent weldability, with low $C_{eq}$ and $P_{cm}$, as well as low components of S and P.

Table 1 shows that the 600 MPa class steels SM570Q, NK-HITEN610U2, and 07MnNiCrMoVDR respectively have lower $C_{eq}$ and $P_{cm}$ than 500 MPa steel 16MnR. However, 800 MPa steel SHY685NS has relatively higher $C_{eq}$ than 16MnR, with equal $P_{cm}$. Besides, the welding materials applying high strength steel are more reliable than they were before.

Table 2 shows general heat input for high strength steel provided by “Welding of High Strength Stee”. The practical welding process of a project should base on the corresponding experiment that supports the welding joint characteristics. According to the Specification for Gate and Penstock of Japan, the heat input should not excess 70 kJ/cm for the 600 MPa class steels, such as SM570Q, SMA570 and SPV450, otherwise, the parameter must be decided by process experiment. In case of 800 MPa class, heat input should not excess 50 kJ/cm and or not excess 45 kJ/cm on average.

Table 3 shows some Chinese projects’ requirement on
technologic parameters, such as pre-heating temperature and heat input, especially stress on controlling heat input to improve the impact toughness ($A_{KVR}$) of welded joint. However, largely increasing tolerance of impact toughness is neither economically, nor quality promised. If the impact toughness, which represents a compositive judge of strength and plasticity, is too high, in some cases the yield stress ($s_y$) might become higher correspondingly, and the critical crack size ($a_{cr}$) become lower. Therefore, the impact toughness of welding joint should promise the basic requirement with some tolerance, but not request it as high as the actual data of the base material.\(^3\)

NDT was also overly requested, and RT dominated the testing. In recent years however, RT has been less applied in testing thanks to UT, which has more strength in terms of crack inspection or likeness. For example, Ming Tombs Project requested 100% UT/\(^{25}\%\) longitudinal weld (10% girth weld) RT. Nevertheless, RT was finally cancelled in the testing on slanted pipe (underground pipe), following the comparison between the two testing results.

Besides, penetrant inspection and magnetic particle inspection are being emphasized on surface defect testing. Furthermore, acoustic emission testing has also begun being used on welding supervision. All these show the recent development on recognizing of testing technology on welded defect of high strength steels.

However, confusing technological requirement with management would cause attending to one thing and losing another. Some technologists and engineers in charge of the projects tend to over highly request on technology because they think it would work even though the process requirement occasionally broken, and this also make quality control easier. Actually, overhigh demand on technology would cause a lot of problems to management, and it also influences the projects negatively, and in many cases the high request is difficult to carry out.

To sum up, when the time and investment are limited for a project, over request on technologic parameters tends to waste time and cost, worsen the working condition, and influence quality control. Take Ming Tombs project for example, heat input was required lower than 30 kJ in its early construction, which eventually caused low efficiency and pressing time limit in its late construction.

What’s more, sometimes it lower people’s guard and become careless in quality control. For example, in a project, part of the welded beam was strictly required in welding process file and passed 100% NDT in RT, UT and MT.
The author thinks, qualified welded joints would be promised on improved working conditions of welding and NDT testing, furthermore, the cost would be reduced and the work would become more efficiently by lowering pre-heating temperatures, less control of heat input, and applying reasonable testing.

Table 4. Test results of strain aging sensitivity for penstock materials.

| Material       | Strength level (MPa) | thickness (mm) | State of sample (J) | $A_{KIC,\text{WC}}$ (J) | $A_{KIC,\text{PEC}}$ (J) | $A_{KIC,\text{PEC}}$ (J) | $\gamma_{\text{Tr}}$ (°C) |
|---------------|-----------------------|---------------|---------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| SHY685NS-F    | 800                   | 52            | Normal              | -                        | 266                      | 270                      | -93                      |
|               |                       |               | Strain aged         | -                        | 268                      | 242                      | -86                      |
| SHY685NS      | 800                   | 42            | Normal              | -                        | 272                      | 265                      | -                        |
|               |                       |               | Strain aged         | -                        | 277                      | 268                      | -95                      |
| NK-HITEN610U2 | 610                   | 60            | Normal              | -                        | (40°C)                   | (40°C)                   | (40°C)                   |
|               |                       |               | Strain aged         | -                        | (40°C)                   | (40°C)                   | (40°C)                   |
| SM570Q        | 600                   | 30            | Normal              | -                        | 308                      | -                        | -                        |
|               |                       |               | 6% strain aged      | -                        | 308                      | -                        | -                        |
|               |                       |               | 8% strain aged      | -                        | 319                      | -                        | -                        |
| 16Mn          | 500                   | 34            | Normal              | 46                       | -                        | -                        | -                        |
|               |                       |               | Cold roll (5/0.025) | 33                       | -                        | -                        | -                        |
|               |                       |               | Cold roll=300°C×1% hot strain | 26 | - | - | - |
| Q235-b (semi killed steel) | 400 | 16 | Normal | 157 | - | - | - |
|               |                       |               | Sampling from a buckled penstock | 15 | - | - | - |

Note: Strain aging condition: 5%--250°C×1h.

Table 5. Test results of strain aging fracture toughness for WEL-TEN80A.

| Test temperature | Loading speed | fracture toughness $K_{IC}/K_{IC}$ (MPa-m$^{1/2}$) | Remark |
|------------------|---------------|---------------------------------------------------|--------|
| 0°C | 0.01 mm/s | Base material | 1% strain aged | 2% strain aged | 3% strain aged | 1% strain aged | 2% strain aged | 3% strain aged | | $K_{IC}$ |
| -40°C | 0.01 mm/s | 288 | 285 | 269 | -- | 271 | 278 | -- | -- | |
| -6°C | 550 mm/s  | 222 | 264 | 281 | -- | 262 | 283 | -- | -- | |
| -40°C | 550 mm/s  | 325 | 232 | 104 | 169 | 291 | 220 | 252 | -- | |

Note: Aging condition: 250°C×1h.

The author thinks, qualified welded joints would be promise on improved working conditions of welding and NDT testing, furthermore, the cost would be reduced and the work would become more efficiently by lowering pre-heating temperatures, less control of heat input, and applying reasonable testing.

3. The Penstock Standards Are behind the Development of High Strength Steel

(1) The current standards are not clarified what requirements could support the new materials, as prevents the application of new materials. The author thinks main technical data, as well as supplemented testing should be specified to support the application of the new materials. In addition, as of the materials less used in practical construction, should be improved on technical requirements. Anyway, a rule supporting the new materials should be set up.

(2) According to the present standards, higher steel strength promises less cold roll deforming, but different materials and qualities with the same strength are not put into consideration. It limited the use of high strength steel in the case of high waterhead and small diameter penstock. In a project, the penstock was hot rolled and reheat treated, and in some projects, the steel structure + steel concrete was used to avoid this problem.

Generally, it’s believed that strain aging is caused by Cottrell Atmosphere, which is formed around the dislocation due to short hall diffusion of atoms N and C caused by decreasing solubility of N and C in the α-Fe, when the steel was cold-deformed. Therefore, the steel improved on its strength and hardness, but lower the plasticity and toughness. The strain aging sensitivity will be decreased if adding a little Al or Ti, for the free N would be fixed in nitride. A minimum strain aging could be obtained by deoxidizing with Al. The present high strength steel, has low components of S and P (see Table 1), as well as high purity thanks to measures that reduces gases in steel, such as vacuum degassing, which improves toughness, and largely reduces strain aging sensitivity (see Table 4).

In Ming Tombs Project, the static fracture toughness test (3-point bending test) and dynamic fracture toughness test (instrumented Charpy test) were implemented to the high strength steel based on its strain aging tensile test and V-Charpy test. The result showed that the strength was improved, elongation lowered, but V-Charpy impact changed less following the cold-deformation and aged treatment. In case of the steel WEL-TEN80A (see Table 5), $K_{IC}$ was not sensitive to strain aging under static loading but its dynamic fracture toughness ($K_{IC}$) was decreased under dynamic loading with loading speed 5 550 mm/s, besides, the $K_{IC}$ with 2% cold deformation accounted for 1/3 of that of the base material at 0°C. In the case of steel SM570Q (see Table 6), $K_{IC}$ with 8% cold deformation had less change following strain aging test, but its $K_{IC}$ with 6% cold deformation or above decreased distinctively at −5°C, and it featured brittle fracture.

However, the current standards specify that higher strength steel allows lower cold rolling deformation, which limits the application of high strength steel in the case of high water head and small diameter pipe. The author thinks,
the application of high strength steel should base on test results, but not take it for granted that the higher strength steel promises smaller cold rolling deformation.

In addition, the results as above, also showed the toughness change could not be fully detected by applying conventional V-Charpy test for their strain aging sensitivity. Anyway, how to properly assess the strain aging effect is still on dispute.

A hot-rolling and a following reheat-treatment is also a solution in the case of high waterhead and small diameter penstock, but many advanced technology applied in manufacture of steel plate could not be reproduced and as a result the mechanical property would be lowered more or less. The author thinks, hot rolling should be avoid if the cold-rolling is proved feasible.

(3) The hydraulic testing is emphasized in the current standards, but in terms of developing trend of penstock technology, it is sort of backward testing and passive after testing, and will be likely cancelled. Therefore, carefully choosing materials, strict technology management and NDT are effective ways of improving structure safety. In the special case when hydraulic testing be considered necessary, using acoustic emission testing could effectively inspect crack growth, and it’s effective to insure the safety of structure.

(4) The standards over-emphasize on relieving welding residual stress. However, they were set for the conditions under conventional materials, low level of welding and NDT technology in the past time. Furthermore, almost all the measures on stress relieving (SR) have their limitation, therefore, SR is generally not performed on high strength steel. In China, this problem has been argued for almost every project about the requirement of standards. Experts have different opinions about SR for thicker parts of penstock in Three Gorges Project. With the reference of WES 2805–1997 “Method of Assessment for Flaws in Fusion Welded Joints with respect Brittle Fracture and Fatigue Crack Growth”, the author’s calculation based on Charp-V impact testing, proved that this structure is safe enough and doesn’t need SR.

Xianshui Project is a good example of this kind. The bifurcation was cancelled hydraulic testing and SR treatment, following discussions and research, and its surface imperfection were grinded carefully, as well as extending NDT was used to insure its safety. This practice provides precious information for the application of high strength steel in Chinese hydraulic stations.

4. Establishing of Economic Comment System for Application of High Strength Steel

Hydraulic Projects applies high strength steel for both structural and economic reasons, but high strength steel is generally over regarded as bad weldability, and overly requested on technology weakened their strength in terms of economic, therefore, a recognizable comment system need to be established in the near future.

5. Conclusion

With the improvement of the technology and management on penstock construction, and the more recognizing about the characteristics of high strength steel plate, high strength steel plate will be more widely used in hydroelectric projects, for its excellent quality and a high capability relative to cost, and promise a bright future.

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