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Development, Experiences and Qualification of Steel Grades for Hydro Power Conduits

In this paper the development and experiences made with the application of high strength steels for penstocks and steel lined shafts for stored and pumping stored hydropower plants is discussed. The evaluation of failure cases showed that high strength steels have to be treated very carefully to assure safe fabrication and service conditions. The results out of those experiences have been introduced in qualification programs which leaded to measures to be applied to allow safe design, manufacturing and service behaviour under static as well as dynamic loading conditions of the conduits.

1 Historical Development of steels for Hydropower Application in Central Europe

Since 1900 in Central Europe penstocks for hydropower plants has been built. As can be noticed from **Figure 1**, **Table 1** and **2**, mainly two grades of steels were used until begin of the 1950s of the last century. After that fine grain steels, normalized, showing higher yield strength up to 400 MPa were introduced. Since about 1960 quench & tempered fine grain Steel grades (Q&T) appeared, showing yield strength up to nearly 600 MPa. With begin of the 1980s the Q&T steel grade S 690 QT was introduced [1].

Thermo-mechanically treated (TM) steel grades 500ML and 550ML firstly were used in Austria in 1988. The first high strength steel grades (HSS) S 690 Q were applied in 2001. HSS TM steel grade S 700 was first applied in the Verbund – AHP Reisseck II Scheme 2010 [2]. In Switzerland for the Cleuson Dixence Scheme the High Strength Steel S 890 QT was used [3]. Similar progress was observed in Japan [4].

When discussing steel grades, the most important issue is the consideration of the joining procedure applied to perform a successful usable penstock. Figure 1 depicts the history of the application of different joining procedures for penstocks and steel lined shafts.

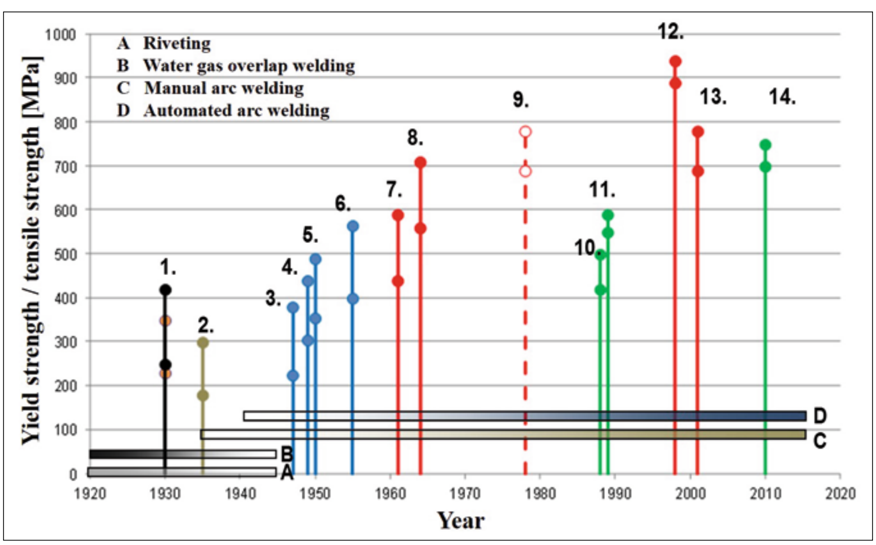

Figure 1: Historical development of steel grades and joining processes for hydropower penstocks and steel lined shafts in Central Europe (Source: [1], [2])

1.1 Applied Joining Processes

In the beginning penstock were made from plates, and joined by riveting. During the twenties of the last century, the so called watergas welding procedure became applicable for the production of pipes. After WW II additionally to the Shielded Manual Arc (SMAW) process the semi-automatic and automatic welding processes MAG, SAW and MIG processes are increasingly in common use.

1.2 High strength steels

When the application of the quenched and tempered (Q&T) fine grain steels started in the late 1950s, hydrogen induced cold-cracking in the heat affected zone (HAZ), the so called type IV-cracking, appeared as the main problem when welding this type of steels (**Figure 2**). The maintenance of proper pre- and post-heating procedures in the cases of cold-cracking was widely underestimated, also the necessity of the use of sensitive non-destructive testing methods [5].

The application of high strength steels, types S 690, and in the last decade also of S 890 QT raised another welding problem, the hydrogen induced cold-cracking in the high strength steel weld metal. The development of high strength weldable steels

Table 1: Steel grades for fusion welded shafts of hydropower plants

Position		Steel	Steel grade	Standard	Yield Point min. [MPa]	Tensile Strength min. [MPa]
1./2.		Mild steels				
3.			StE255		255	360
4.	blue	Normalized Steel Grades	StE315	DIN 17 102 (10/1983)	315	440
5.			StE355		355	490
6.			StE420		420	530
7.			S460Q		460	550
8.	red	Quenched and Tempered	S550Q	DIN EN 10 025-6	550	640
9./13.			S690Q		690	770
10.	green	Thermomechanically Rolled	S420MC	DIN EN 10 149-2	420	480
11.			S550MC		550	600
12.	red	Quenched and Tempered	S890Q	DIN EN 10 025-6	890	940
14.	green	Thermomechanically Rolled	S700MC	DIN EN 10 149-2	700	750

made great progress in the last 20 years by the application of the combination of lean alloying concepts with the thermo-mechanical treatment of the materials. As a result of this successful development, steel grades showing excellent strength and toughness properties, but also good weldability appeared on the market. The risk of H–induced cold-cracking in the HAZ was dramatically reduced which, as a consequence, leads to the reduction of applied preheating temperatures. By the use of the traditional fusion welding procedures SMAW and SAW, the required strength in the weld deposit adequate to that of the base material can only be reached by the application of a higher amount of alloying elements in the consumables. By this, the risks of the appearance of H-induced cold-cracking moved from the HAZ region of the base material towards the weld deposit. The H–induced weld metal cold cracking appeared mostly as transversal but also as longitudinal cracks in the weld deposit as shown in **Figure 3**. These types of cracks were unexpected and therefore in many cases not detected by the applied traditional non-destructive testing (NDT) methods.

The cause of these cracks is, as in the traditional HAZ-type IV cold-cracks, the combined interaction of microstructure, H-content and residual stresses. The maintaining and control of the necessary pre- and post-heating temperatures and durations, the control of the H-intake by the consumables, are in combination with the application of proper NDT-methods in the case of using high strength steel grades of even greater importance as it was in the past (Figure 3). One landmark of the underestimation of these basic requirements when using new high strength grades is the Cleuson Dixence case in Switzerland, which happened in December 2000. The detailed results of these investigations are described in [3].

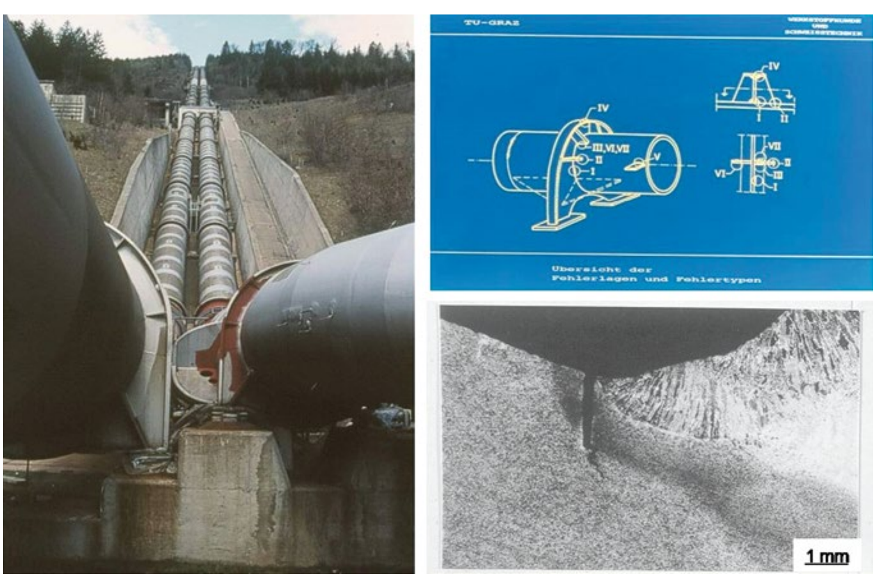

Figure 2: Type IV cold cracking on penstock Q&T fine grain steel (Source: [5])

2 Qualification criteria for high strength steel grades for hydropower application

Based on these experiences, a new approach for the definition of qualification criteria when using high strength steel grades for hydropower application was developed. The criteria which have to be considered for the selection of high strength steel grades for design, fabrication and service of penstocks and steel lined shafts to assuring its integrity are, beside of the weldability and application of adequate fabrication procedures: strength and toughness for static loading conditions, fatigue properties for dynamic loading conditions, susceptibility for stress corrosion cracking and application of optimal non-destructive testing methods and sequences.

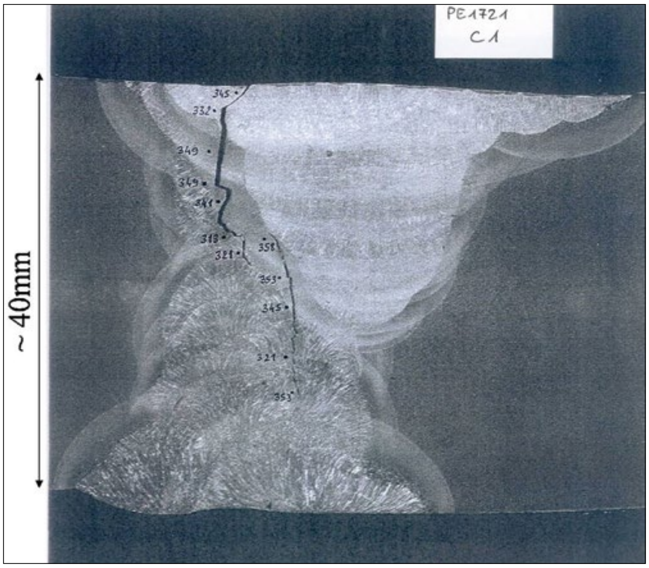

Figure 3: H-induced cold crack in S 890 steel weld deposit (Source: [3])

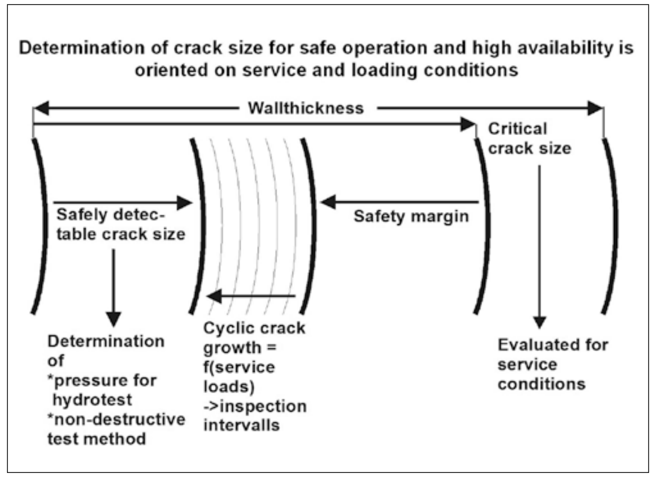

Figure 4: Integrity analysis (Source: [6])

2.1 Static Loading Conditions

2.1.1 Strength

The designers and stress analysts see at their first criteria the strength properties: These are very important and standardized in the codes. Allowable stresses and so called safety factors are relatively easy to control and derivations from the specified values are easy to observe, even for economists and lawyers.

2.1.2 Toughness

Much more important for the integrity of the component is the capability of the material to keep local overstressing through plastic deformability by the inherent high toughness; this not only for the specified service conditions but also for unexpected service events or even catastrophic natural disasters. This is necessary not only for the base material, but also for all different microstructures present in the component, caused by fabrication processes like welding, forming and repairs.

The material property which describes that behaviour is the toughness. Standards usually define toughness criteria by specified minimal notch impact values, which have to be fulfilled during the acceptance tests. Charpy impact testing is a very sensitive and valuable test method to check the proper production procedure of the material. But the results of that test cannot represent quantitatively the integrity of the component to bearing loads in presence of flaws, i.e. cracks. Additional application of fracture mechanics approaches is recommendable.

2.2 Qualification Programs to allow Integrity Analysis

For the representation of the qualification criteria so called Qualification Programs were developed and performed to allow an Integrity analysis [3], [6], [7], [8], [9], [10]. Safe design of components shall be based on the principles of the Integrity Analysis, briefly described in Roos et. [6] (**Figure 4**).

The detectable crack size always have to be smaller compared to the critical crack size in the fabricated condition of the component as well as in service, in case of the propagation of an existing crack or evolution of a fatigue crack.

Fortunately in the last decades the fracture mechanics approach matured and gives, when qualified applied, very helpful advice about the integrity of components containing flaws under given loads. This is valid not only for homogenous material, but also for the fact of the presence of flaws in the material, represented conservatively by sharp cracks.

The results obtained from the Qualification Programs allowed defining the material properties of the new grades of high strength steels which allow quantifying the integrity of components in presence of flaws, which can safely be detected by non-destructive tests applied.

During those Qualification Programs not only small fracture mechanics samples were tested, but also the integral behaviour of welded plates by testing of wide plate tests.

Figure 5 as an example depicts as a result from such a program the influence of different toughness levels on the critical crack size in a pipe under given design and pressure assumptions.

By using the material data achieved by fracture mechanics tests critical crack sizes for the different positions in the shaft can be estimated and therefore allow a quantitative integrity analysis.

2.3 Reversible temper embrittlement treatment (RTE)

Weld deposit of high strength steel welds may, under certain circumstances, suffer from a severe embrittlement reaction caused by non-qualified post weld heat treatment (PWHT) procedures applied on welded components during fabrication. This effect is called “temper embrittlement” (TE) [11]. Temper embrittled weldments causes a high risks of brittle fracture during pressure test and/or service of the component. Therefore it should be prevented in any case.

Recent research performed showed, that weld deposit of high strength steel, which suffered from temper embrittlement can recover the toughness by application of a controlled local heat treatment in the range of 600 °C peak temperature for very short times, even less than 1 minute. This effect is called reversible temper embrittlement (RTE). **Figure 6** shows the effect of RTE treatment on a TE embrittled weld deposit of a high strength steel, by ap-

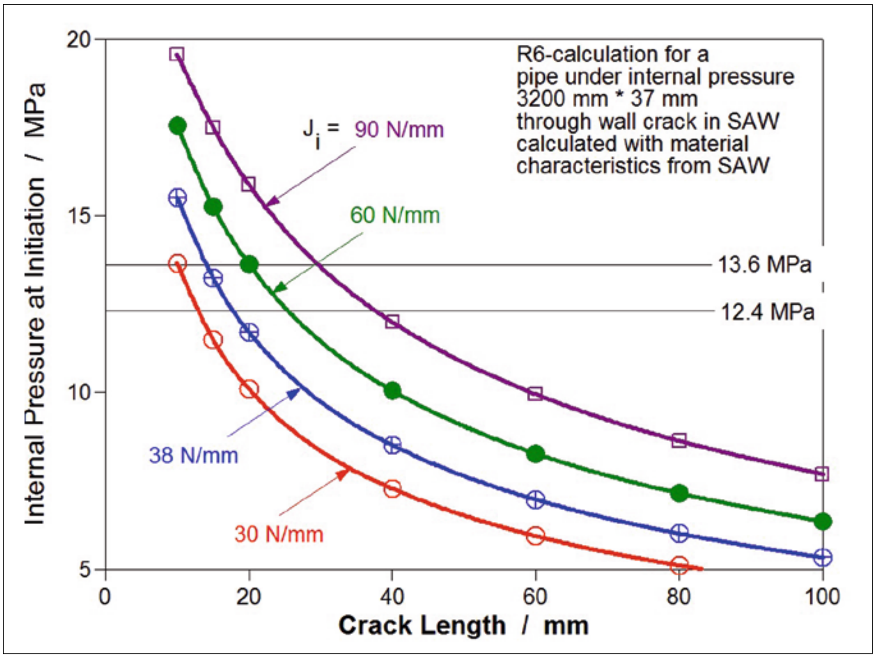

Figure 5: Initiation pressure of a pipe depending of through wall crack length and different initiation values calculated with R6 method (Source: [6])

plication of a peak temperature of around 600 °C for 15 seconds.

Of course, temper embrittlement of weld deposit shall anyway be prevented by application of qualified PWHT and controlled by testing of working procedure tests which exactly undergoes the PWHT sequence of the component.

In case of detection of that dangerous effect in an already welded component, under special controlled conditions, the toughness of the weld deposit can principally be rehabilitated by application of a qualified RTE treatment.

2.4 Dynamic Loading Conditions

In the past the design of penstocks and conduits at least in Austria, was based mainly on static loading approach [2]. Because of the dramatic change of the requirements on the service program of Stored Power Plants (SP) and Pumped Storage Power Plants (PSP) coming from the power grids, the increasing use of high strength steels in the recent years, the item of dynamic loading of penstocks and steel lined shafts became nowadays one of the main issues for the design of new as well as for the life time assessment of existing penstocks. Because the fatigue strength of high strength steels is more or less independent from the yield strength of the steel in the endurance domain, penstocks and lined shafts made from high strength steels are more sensitive to undergo fatigue damage compared to lower strength materials. Recent investigations showed [12] that beside of the needs to know more about the quantitative fatigue behaviour of that materials as base material properties itself as well as in the welded condition, the influence of the fabrication quality of the penstocks and steel lined shafts has decisive influence on the fatigue lifetime of such components. Angular as well as linear misalignment of the welded shells can have dramatic influence on the local stresses in the notch region of welds. When using the common IIW Approach, the calculated life time exhaustion factor, described by a Miner damage sum, taking into account a given service program of pressure fluctuations, is therefore also very much dependent from the geometric situation of each single welded shell. The calculation reveals that even an angular misalignment which is in accordance to the widely used CECT recommendation can reduce the calculated life time in relation to an ideal circular cross section of the pipe significantly [12] (**Figure 7**).

2.5 Non-Destructive Testing

The use of HSS for Penstocks and steel lined shafts requires, after the experience of the authors, in addition to the common NDT procedures generally applied when fabricating safety related designs, some additional measures to assure the needed homogeneity of the welded joint. The appearance of H–induced cracking in the weld deposit and the possibility of delayed cracking have to be considered by application additional and delayed ultrasonic testing (UT) procedures.

3 Conclusions and Recommendations

Penstocks and steel lined shafts for SP an PSP are engineering designs which are exposed to high loadings during service and keep an inherent high risk potential for human life and goods in case of collapse or leakages. In addition, traditionally a lifetime of 100 years is expected. These criteria make penstocks and steel lined shafts of SP and PSP in relation to many other engineering to palmary designs in the history and practice of engineering services.

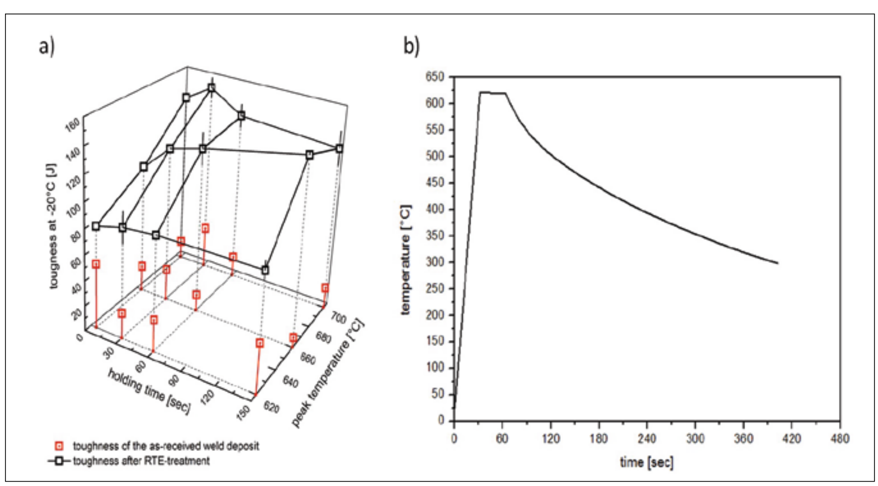

Figure 6: Toughness increase (a) due to applied reverse temperature embrittlement treatment (RTE-HT) according to (b) (Source: Authors)

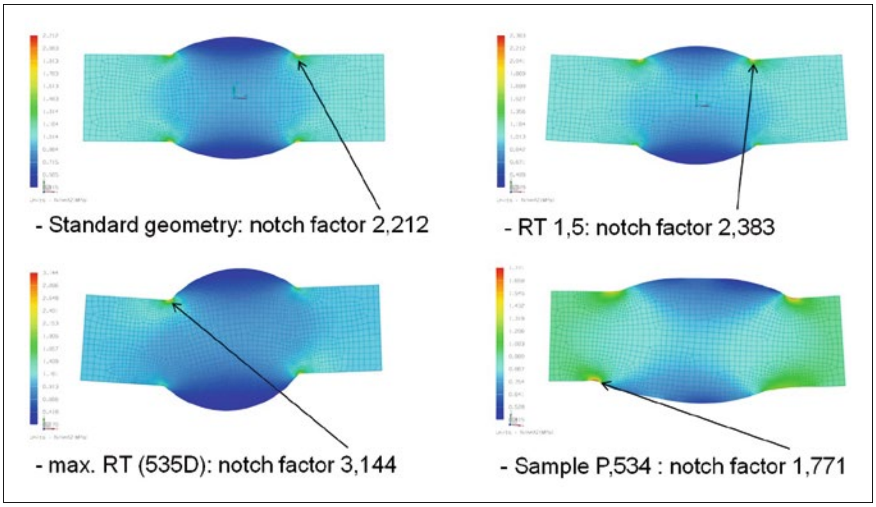

Figure 7: 2D simulation of notch factors of different weld geometries showing different roof toppings (RT) (Source: [12])

When planning, designing, ordering and fabricating such components the responsible people involved in that business shall acknowledge this fact and accept their responsibility. They have to have in mind, that, beside of the specified service program, many unexpected situations during the very long service period can happen which have to be carried by the component. Regarding the penstocks and lined shafts, we as the responsible people involved have to respect not only the existing design materials and testing standards, but also have to recall the experiences, which were made worldwide in the past. The event which was the nucleus for the new approach of qualification of new grades of HSS for hydropower plants is a very good example of respecting that experience.

In the last decades outstanding developments in the field of strength of high strength steels grades happened and allowed the design, fabrication and erection of huge SP and PSP. Also because of the new requirements coming from the grids, new challenging dynamic service conditions appeared and requires higher exploitation grades of the penstocks and lined shafts. In addition to the static load also the dynamic loading conditions have to be considered. Extensive Qualification Programs were performed to quantify the fabrication and service properties of the materials applied.

The conclusions out of these investigations as well as of the first fabrication experiences show that these new HSS grades behave very sensitive. This requires a fully new approach to assure that all precautions necessary during design, material selection, planning and performance of the fabrication steps, especially welding, assembly and testing, as well as in the service adhered. If these conditions, based on an integrity analysis, are completely fulfilled, a successful and safe service for a long time can be assured.

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References

[1] Starnberger, R.: Personal communication, 2014.
[2] Stering, P.; Mayrhuber, J.; Cerjak, H.: Pressure Shaft Steel Linings for HPP, Development in recent VERBUND projects in Austria. In: 3rd Intl. Conference on High Strength Steels for Hydropower Plants, Graz, 2013.
[3] Cerjak, H.; Enzinger N. (eds.): Proceedings Intl. Conference on High Strength Steels for Hydropower Plants, Graz, 2005.
[4] Proceedings 2nd Intl. Conference on High Strength Steels for Hydropower Plants, Takasaki, Japan, 2009.
[5] Cerjak, H.; Horn, H.; Seibold, A.: Metallkundliche Methoden zur Unterscheidung von Kaltrissen/Ermüdungsrissen an einer Schweißkonstruktion aus hochfestem niedriglegiertem Stahl. In: Prakt. Metallographie, 1989.
[6] Roos, E.; Stadtmüller, W.; Cerjak, H.; Dimmler, G.: Results of Fracture Mechanics Investigations on Steel S890 and its Weldments. In: Proceedings Intl. Conference on High Strength Steels for Hydropower Plants, 2005.
[7] Cerjak, H.-H.; Chene, O.; Enzinger, N.; Roos, E.: Qualification Program for the Rehabilitation of Cleuson-Dixence: Requirements and Results. In: Pre-prints of the Papers Conference High Strength Steels for Hydropower Plants (2009), S. 2.1-2.6.
[8] Mayrhuber, J.; Kirilowitsch, Ch.; Cerjak, H.; Enzinger, N.: Qualification Procedure of Thermomechanical Steel Alform 700 for Pressure Shaft Lining of Reisseck II pumped Storage HPP. In: 3rd Intl. Conference on High Strength Steels for Hydropower Plants Graz, 2013.
[9] Fraunhofer IWM (ed.): VERB Failure Assessment Software. Version 8.0. Freiburg, 1988-2011.
[10] BS 7910: Guide on methods for assessing the acceptability of flaws in metallic structures, 1999.
[11] Erwin, J. C.; Kerr, J. G.: Welding Research Council NY, USA, V. 275, 1982.
[12] Demal, R.; Moser, C.: Fatigue Assessment of Hydropower Plants Penstocks using IIW-notch stress concept. In: 3rd Intl. Conference on High Strength Steels for Hydropower Plants, Graz, 2013.

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Entwicklungen, Erfahrungen und Qualifikation von Stählen für Wasserkraftwerke

In diesem Beitrag werden die Entwicklungen und Erfahrungen in der Anwendung von hochfesten Stählen für Druckschächte von Speicher- und Pumpspeicherkraftwerken diskutiert. Die Beurteilung von Schadensfällen hat gezeigt, dass hochfeste Stähle bei sehr sorgfältiger Verarbeitung sicher eingesetzt werden können. Die Erfahrungen aus solchen Untersuchungen sind in Qualifikationsprogramme eingeflossen, welche Maßnahmen beschreiben, die für Auslegung, Herstellung und den sicheren Betrieb unter statischer und dynamischer Belastung notwendig sind.