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EVALUATION OF HARDNESS LEVELS OF T24 BOILER TUBE BUTT WELDS REGARDING SCC SUSCEPTIBILITY IN HIGH TEMPERATURE WATER

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ABSTRACT

In Europe between 2006 and 2012 several ultra-super-critical (USC) coal-fired power plants were built employing T24 (7CrMoVTiB10-10 / DIN EN 10216-2:2014-03 / VdTÜV sheet 533/2) in membrane walls. During commissioning stress corrosion cracking (SCC) on the tube-to-tube butt welds appeared. The widespread damages required the development of a new patented commissioning procedure to avoid recurring damages [1]. Although this commissioning procedure was employed successfully and the power plants are in operation since then, a debate about the implementation of a hardness limit for such butt welds was initiated. According to the European standards butt welds of T24 boiler tubes with wall thickness < 10 mm (0.3937 in) do not require any post-weld heat treatment (PWHT) and no hardness limits are given [2-3]. When looking at manufacturing related issues such as an imminent risk of cold cracking after welding of micro-alloyed steels a widely applied but coarse hardness limit is 350 HV [4]. Based on laboratory tests, some authors reallocated this 350 HV hardness limit for addressing SCC susceptibility of low-alloyed steels [5]. This article describes typical hardness levels of T24 boiler tube TIG butt welds and the SCC behavior in high temperature water. Further the effect of the stress relief heat treatment (SRHT) of the boiler membrane walls between 450 °C and 550 °C (842 °F and 1022 °F) on its hardness values and on the SCC behavior is discussed, showing that the hardness values should not be used as an indicator for SCC susceptibility of T24 boiler tube butt welds.

KEYWORDS

T24 boiler tubes, 7CrMoVTiB10-10, membrane walls, welding, stress corrosion cracking, hardness, stress relaxation, high temperature water, heat treatment

INTRODUCTION

The latest generation of ultra-super-critical coal-fired power plants built in Germany and in the Netherlands entered commercial operation within the past three years. In several cases the power plant commissioning phase was interrupted by a widespread SCC damage on the tube-to-tube butt welds of the T24 (7CrMoVTiB10-10 / DIN EN 10216-2:2014-03 / VdTÜV sheet 533/2) membrane walls (Fig. 1). This phenomenon required a fast reaction of the parties involved and a new patented commissioning procedure was put in place to avoid recurring damages. The key actions of the patented commissioning procedure were:

- a stress relief heat treatment (SRHT) of the boiler membrane walls around 500 °C (932 °F)
- strict limitation of the dissolved O_2-Level according to the VGB guideline
- strict observance of feed water quality
- no long term operation between 150 °C and 280 °C (302 °F and 536 °F)
- reduction of chemical cleaning scope

These measures have proven to be successful in avoiding SCC on T24 membrane wall butt welds. One of the main targets of the actions employed was to reduce the stresses originating from manufacturing and assembly of the membrane walls by performing a so called stress relief heat treatment of the boiler prior to its first operation. This measure consists in heating up the boiler with the help of external oil-fired burners and reaching 500 °C (932 °F) in the T24 membrane walls for a period of at least 24 hours. By doing so, the stresses especially on and around the tube-to-tube butt welds will be reduced by relaxation. A simulated stress relaxation of the T24 material at 550 °C (1022 °F) is shown on Fig. 2.

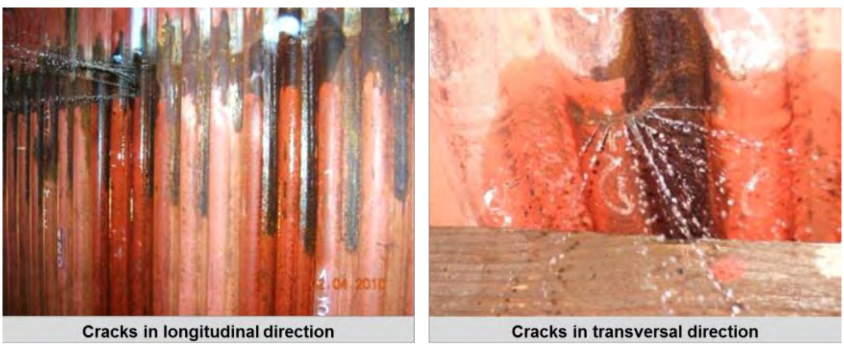

Figure 1: Stress corrosion damages on T24 membrane wall tube-to-tube butt welds during commissioning

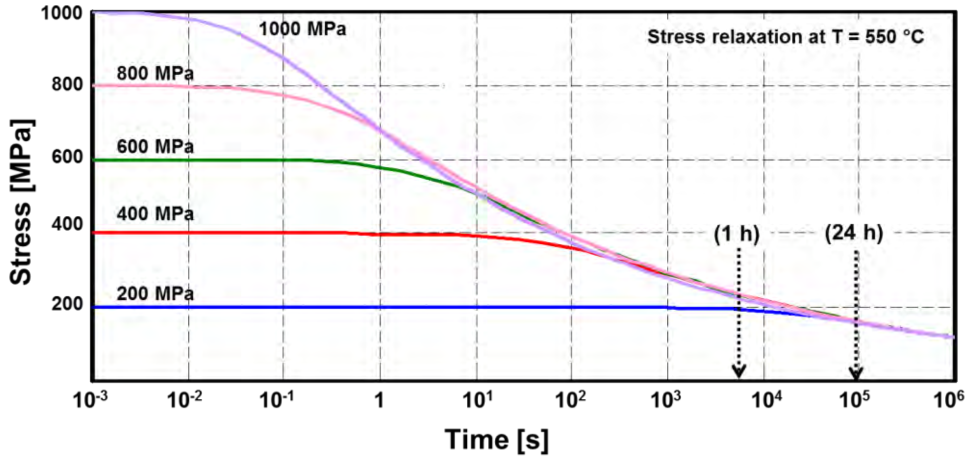

Figure 2: Simulated stress relaxation of the T24 over time at 550 °C (1022 °F)

Even though all power plants with T24 membrane walls reached commercial operation successfully, a discussion about the implementation of hardness limits for such butt welds was initiated. According to the European standards butt welds of T24 boiler tubes with wall thickness < 10 mm (0.3937 in) do not require any post-weld heat treatment (PWHT) and no hardness limits are given [2-3]. The qualification of T24 according the European pressure directive was performed with results of several R&D-projects in which utilities, tube manufacturers, steel mills, welding companies and boiler manufacturers were involved. The qualification also included tube-to-tube butt welds having maximum hardness values in the heat affected zone (HAZ) around 370 HV [6]. The field experience from several power plants shows that the hardness of actual tube-to-tube butt welds in membrane walls, consisting of a three-layer manual TIG-weld, ranges between 280 HV and 380 HV. In some cases single values can reach approximately 400 HV.

These facts lead some parties to demand the implementation of a hardness limit of 350 HV for T24 butt welds, regardless to the fact that this hardness limit is actually intended to address manufacturing related issues such as an imminent risk of cold cracking after welding of micro-alloyed steels. The demand is supported by the reallocation of this 350 HV hardness limit to the SCC susceptibility by Hickling [5]. His hypothesis was based only on laboratory results of base materials and limited to hydrogen induced SCC damages. In his conclusions he mentioned 400 HV as a possible empirical limit for welded joints. In the case of T24 few experimental data regarding a possible correlation between hardness and SCC is known. Some authors have shown that a stress relief treatment of T24 can reduce the SCC appearance in laboratory tests without reducing the hardness of the material [7].

Furthermore, a common misunderstanding is that a heat treatment such as the described SRHT between 450 °C and 550 °C (842 °F and 1022 °F) will irrefutably lead to a reduction of the hardness of T24 butt welds. This paper explores the experiences with T24 membrane wall boiler tubes, addressing their typical hardness levels and their SCC behavior in high temperature water. Additionally the effect of a stress relief heat treatment (SRHT) between 450 °C and 550 °C (842 °F and 1022 °F) on the hardness of T24 butt welds is discussed and put in relation to their SCC behavior in high temperature water.

MATERIAL AND EXPERIMENTAL

Material – Manual TIG boiler tube butt welds

For the experiments T24 (7CrMoVTiB10-10 / 1.7378) boiler tubes according to DIN EN 10216-2:2014-03[8] with 44.5 mm (1.75 in) outer diameter and 6.3 mm (0.248 in) wall-thickness were selected as sample material. Tube-to-tube butt welds (three-layer manual TIG-weld) were manufactured from 150 mm long tube segments using a valid welding procedure specification (WPS), which also was used for manufacturing of T24 membrane walls. A commercially available filler metal with a rod diameter of 2.4 mm (0.094 in) was employed. The chemical composition of the boiler tube material and filler metal are summarized in Table 1. After the manufacturing, a nondestructive testing using penetrant testing (PT) and X-rays (RT) was performed.

Subsequently longitudinal cross sections and 3-point bending samples (Jones-samples) according to DIN 50915:1993 [9] with a KB5 geometry were machined from the 300 mm (11.811 in) long tube-to-tube butt welds.

Table 1: Chemical composition of the T24 boiler tubes and filler metal employed

Chemical analysis of boiler tubes in %										
	C	Si	Mn	P	S	Cr	Mo	Al	Ti	V
Min.	0.05	0.15	0.30	-	-	2.20	0.90		0.05	0.20
Max.	0.10	0.45	0.70	0.020	0.010	2.60	1.10	0.020	0.10	0.30
T24 boiler tubes	0.09	0.25	0.54	0.010	0.004	2.47	0.97	0.013	0.07	0.23

Chemical analysis of filler metal in %												
	C	Si	Mn	P	S	Cr	Mo	Nb	V	Cu	Ti	B
Filler metal	0.08	0.19	0.58	0.008	0.003	2.60	1.00	0.055	0.229	0.02	0.002	0.0002

Heat treatments and hardness measurements

The heat treatments were performed according to the SRHT procedure with temperatures between 450 °C and 550 °C (842 °F and 1022 °F) and finalized by an air cooling of the samples. A further heat treatment at 730 °C (1346 °F) for 1 hour and air cooling of the samples was performed to simulate a post weld heat treatment (PWHT) as specified in the DIN 12952-5:2012 [10] and VdTÜV sheet 533/2 for wall thickness greater 10 mm (0.3937 in).

Hardness tests according to DIN EN ISO 6507-1:2006-03 [11] using a load of 9.807 N (HV1) were performed on cross sections of the samples prior and after the heat treatments.

SCC tests in high temperature water

For the SCC tests static autoclaves with a volume of 1 liter and a temperature range between room temperature and 300 °C (572 °F) were employed. All tests were performed at 180 °C (356 °F) under simulated feed water conditions, using fully demineralized water with pH-value 9.5 via ammonia addition and an increased dissolved oxygen content (dissolved O_2 > 2 ppm). The maximum test duration was 250 hours. After the SCC test a visual inspection was performed, sometimes followed by cross sections to confirm the result.

As already mentioned, the 3-point bending samples for the SCC tests were machined according to DIN 50915:1993 using the KB5 geometry, with the butt weld in the center of it (Fig. 3). The inner tube surface was tested in the "as manufactured" condition by bending the samples over the extrados with a defined deformation. The deformation level referring to a deflection of a = 5 mm according to the standard resulted in a plastic deformation and in additional axial stresses at the weld root.

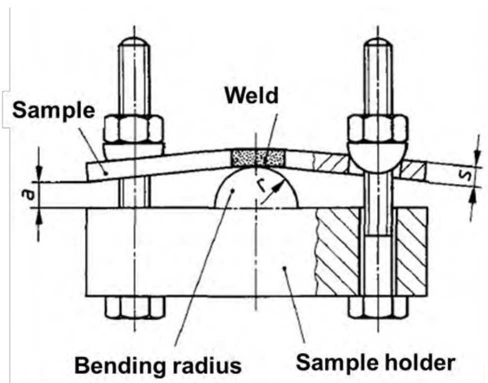

Figure 3: 3-point bending samples according to DIN 50125:1993 using the KB5 geometry and deformation level a = 5 mm

EFFECT OF STRESS RELIEF HEAT TREATMENT ON HARDNESS

Typical hardness of T24 manual TIG butt welds

For the base material of T24 of membrane wall boiler tubes the usual hardness values were located between 190 and 220 HV. Investigations of T24 membrane wall welds revealed that hardness values range between 220 HV and 380 HV for the HAZ and between 280 HV and 380 HV for the weld itself. In some cases single values can reach 400 HV. Figure 4 presents the usual scatter-band for hardness values in the base material, HAZ and weld material. The hardness profiles on cross sections of two different T24 butt welds reveal the potential hardness differences (Fig. 5).

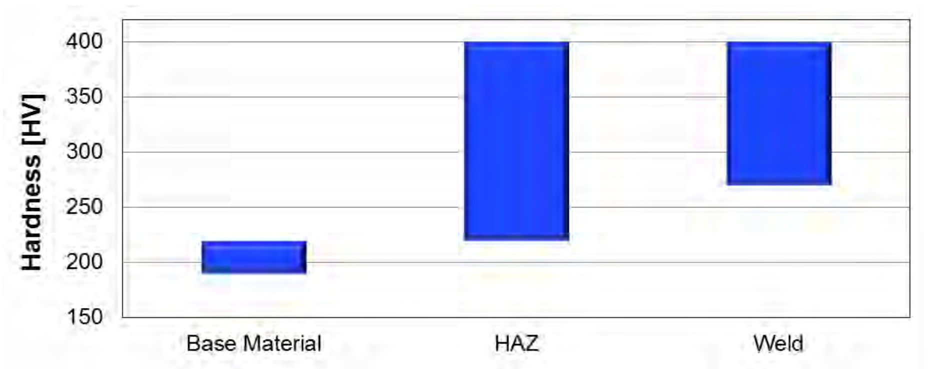

Figure 4: Scatter-band of the hardness of base material, HAZ and weld metal measured on T24 membrane wall tube-to-tube butt welds

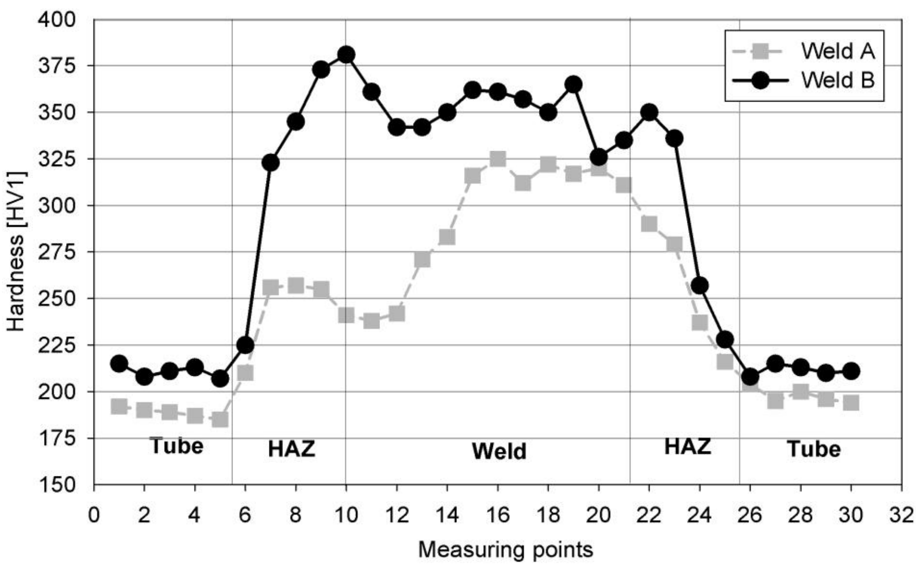

Figure 5: Hardness profiles of the root layer of two different T24 butt welds

Influence of heat treatments on the material hardness

An assessment of the hardness values after SRHT procedures with temperatures between 450 °C and 550 °C (842 °F and 1022 °F) has shown that the scatter-band of the HAZ and the weld (Fig. 4) will remain almost unchanged for the heat treatment duration of 24 hours. Also longer heat treatment durations have little effect on the hardness values. This was also discussed by other authors for a temperature of 550 °C (1022 °F) and heat treatment durations up to 3000 hours [12]. Surprisingly when looking at a single sample and performing hardness measurements before and after SRHT, the resulting scatter-band of Fig. 4 gets much smaller and a slight rise of the hardness values can be seen (Fig. 6 and 7). The mean hardness rise reaches approximately 7 % in the HAZ and about 12 % in the weld itself, corresponding roughly to additional 30 HV. The results from an actual SRHT on boiler membrane walls of a power plant (labeled "Field exp. 450°C-500°C/55h" in Fig. 6 and 7) were according to these findings. Similar results were recently published by Metzger, who likewise indicated an increase in hardness up to 30 HV due to a SHRT between 470 °C and 500 °C (878 °F and 932 °F) [13]. This hardness rise is related to the secondary hardening effect by precipitation of carbides at temperatures greater than 450°C (842 °F).

This secondary hardening by precipitation of carbides loses its positive influence if the material is exposed to higher temperatures such as the one for a PWHT at 730 °C (1346 °F). The results in Fig. 6 and 7 confirm this behavior. The mean hardness drops about 24 % in the HAZ and up to 30 % in the weld itself, corresponding to a mean hardness reduction of 80 HV. Restating that the PWHT is only required for wall thickness greater 10 mm (0.3937 in) according to the DIN 12952-5:2012 [10] and VdTÜV sheet 533/2 and therefore not required and usually not applied for membrane walls.

EFFECT OF STRESS RELIEF HEAT TREATMENT ON SCC BEHAVIOR

Former investigations performed by Husemann *et al* and Devrient *et al* revealed that T24 tube-to-tube welds can develop SCC in high temperature water with increased oxygen levels [14 - 16]. The SCC tests were performed simulating operational conditions of power regarding feedwater chemistry, temperature and deviations of the required dissolved oxygen concentrations. The authors proved that SCC will only occur if the dissolved oxygen levels are above the limits specified by valid standards, being aggravated by rising oxygen levels.

Taking these facts into consideration, the SCC tests presented in this article were performed under known critical conditions for T24 tube-to-tube welds. The samples were exposed to high temperature water at 180 °C (356 °F), pH 9.5, with a dissolved oxygen concentration > 2000 ppm for a maximum duration of 250 hours. The results are summarized in Table 2.

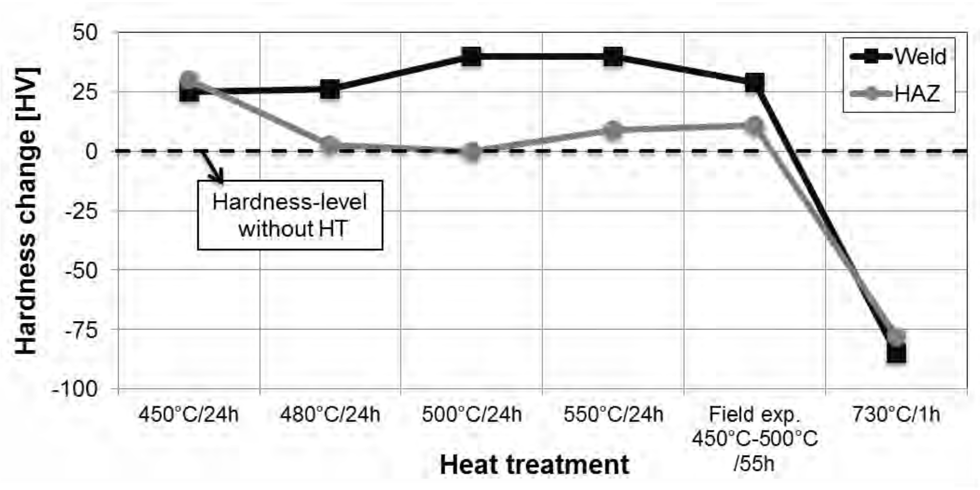

Figure 6: Relative hardness change of single T24 samples due to SRHT at different temperatures. The results "Field exp. 450°C-500°C/55h" refer to samples from an actual power plant before and after SRHT

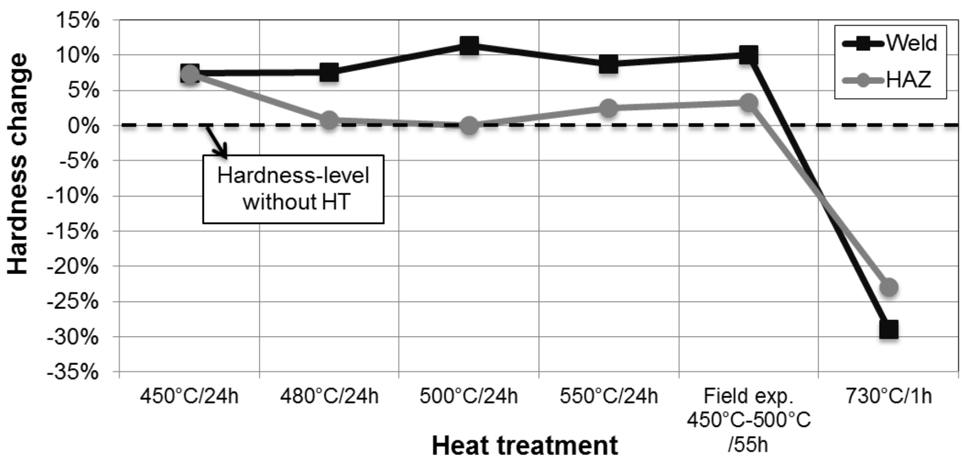

Figure 7: Percentage hardness change of single T24 samples due to SRHT at different temperatures. The results "Field exp. 450°C-500°C/55h" refer to samples from an actual power plant before and after SRHT

Under these critical conditions 60 % of the samples without any heat treatment presented SCC damages. The simulated SRHT at 450 °C (842 °F) in bent condition (deformation was applied prior to the SRHT) lead to no improvement of the SCC behavior. On the other hand higher temperatures from 500 °C to 550 °C (932 °F and 1022 °F) had a positive effect reducing the SCC rate to 0 %. The same effect was reached by the PWHT at 730 °C (1346 °F).

Table 2: SCC cracking rate of 3-point bending samples in high temperature water at 180 °C (356 °F), pH 9.5, with a dissolved oxygen concentration > 2000 ppm for samples without heat treament, with SRHT at different temperatures or PWHT at 730 °C (1346 °F)

	No HT	450 °C / 24 h	500 °C / 24 h	520 °C / 24 h	550 °C / 24 h	730 °C / 1 h
SCC	60%	100%	17%	0%	0%	0%
No SCC	40%	0%	83%	100%	100%	100%

Based on the results of the SCC tests the employed SRHT presents itself as one reliable measure to reduce the risk of SCC during commissioning of new-built power plants with T24 membrane walls. The positive effect of SRHT is specially required when detrimental environmental conditions such as high dissolved oxygen level in the feedwater at temperatures between 150 °C and 280 °C (302 °F and 536 °F) are expected.

CORRELATION OF HARDNESS AND SCC BEHAVIOR

The results revealed that the positive effect of SRHT on the SCC behavior of T24 tube-to-tube butt welds is related to the relaxation of residual stresses (Fig. 2). Depending on the SRHT treatment the hardness values can rise up to 7 % in the HAZ and up to 12 % in the weld itself showing that there is no correlation between hardness and the SCC behavior. Also the field experience from different power plants, where SRHT was applied, confirms these findings. The results are in agreement with the recently published work of Metzger, which noticed a reduction of residual stresses, a rise in hardness and a positive influence on SCC behavior after an SRHT at 480 °C (896 °F) for 48 hours [13].

Especially if the implementation of hardness limits as acceptance criteria is discussed, then rise in hardness by SRHT must be considered. For instance if 380 HV would be considered as maximum acceptable hardness for welds without heat treatment, a limit of 400 HV to 410 HV would be required after SRHT. Lower hardness values can only be achieved if a PWHT between 720 °C and 760 °C (1328 °F and 1400 °F) is applied.

CONCLUSIONS

The results of the investigations performed presented that the hardness of T24 tube-to-tube butt welds will rise up to 7 % in the HAZ and up to 12 % in the weld itself when a SRHT between 450 °C and 550 °C (842 °F and 1022 °F) is applied for a period of 24 to 55 hours. The SRHT leads to a clear reduction of the SCC appearance in high temperature water, which is mainly related to the reduction of residual stresses by relaxation processes. No correlation between hardness values and SCC behavior of T24 tube-to-tube butt welds was found, which is in accordance with the results of other authors [7,13]. All findings were confirmed by the experience in the field with actual SRHT at different power plants.

If the implementation of a hardness limit for T24 tube-to-tube butt welds with wall thickness smaller than 10 mm (0.3937 in) (application in membrane walls) is considered, then the rise in hardness by SRHT must be taken into account. If 380 HV would be proposed as maximum acceptable hardness for welds without heat treatment, a limit of 400 HV to 410 HV needs to be considered as acceptable after SRHT. A noticeable hardness reduction can only be attained via PWHT between 720 °C and 760 °C (1328 °F and 1400 °F), but this treatment has proven to be not required to minimize the SCC occurrence of T24.

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