Effect of increasing post weld heat treatment temperature on the fracture toughness of an ASME SA-542M steel

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ABSTRACT. The ASME SA-542/SA-542M steel is currently used for various large size, heavy thickness components that must withstand severe service conditions in the petrochemical industry.

Frequently in field welding operations have to be carried out either for fabrication or repairing purposes; as a consequence, a Post Weld Heat Treatment is required to stress relieve both the weld metal and the heat affected zone, and to decrease their hardness. This PWHT unavoidably results in a further tempering treatment also of the base metal whose hardness and mechanical strength are further diminished. In addition, in field PWHT are not simple to carry out; heating panels are used, consisting of electrical resistances, embedded in ceramic tiles, under a proper insulation. Notwithstanding each panel is controlled by a thermocouple, temperature may vary from zone to zone, and even under a single panel differences of +/- 5° C can be recorded. Furthermore, K type thermocouples that are usually used have an allowable max. error at the PWHT temperature of 0.5%.

Furthermore, also in the case of furnace treated components, considering the large size of the furnaces, the position of the heating burners, the fluido-dynamics of the heating fumes, etc., it cannot be excluded that some zones may experience maximum temperatures somewhat higher than the prescribed one.

Under these premises, tempering of base metal at temperatures higher than the prescribed level cannot be excluded; over tempering not only produces a solution-reprecipitation of carbides, which increase their size and are increasingly located at grain boundaries, but may also promote an increase of the ferrite grain size. All these microstructural modifications may impair the toughness properties of the base metal, because of their detrimental effect on the fracture behavior at low temperatures.

In the present research work fracture toughness measurements have been carried out on an ASME SA-542/SA-542M steel subjected to different tempering conditions to assess the effect of treatment temperatures higher than the maximum level for PWHT on either microstructure and toughness.

SOMMARIO. L'acciaio ASME SA-542/SA-542M è attualmente utilizzato per vari componenti di grandi dimensioni e spessore, che devono resistere a condizioni di servizio severe nel settore petrolchimico. Spesso per la loro fabbricazione o riparazione, talune operazioni di saldatura devono essere eseguite sul campo, e di conseguenza è necessario ricorrere ad un trattamento termico post-saldatura per distendere sia il cordone di saldatura sia la zona termicamente alterata al fine di diminuirne la durezza. Tale PWHT inevitabilmente si traduce in un ulteriore trattamento di rinvenimento anche del metallo di base, la cui durezza e resistenza meccanica sono ulteriormente diminuite. I PWHT in campo non sono semplici da effettuare; per tali trattamenti sono utilizzati pannelli riscaldanti, costituiti da resistenze elettriche, incorporate in ceramica, con un adeguato isolamento. Nonostante ciascun pannello sia controllato da una termocoppia, la temperatura può variare da zona a zona, e differenze anche di +/- 5 °C si possono registrare in un singolo pannello. Inoltre, le termocoppie di solito usate sono di tipo K ed hanno un errore max ammissibile, alla temperatura di PWHT, dello 0,5%.

Inoltre, anche nel caso di componenti trattati in forno, in considerazione delle grandi dimensioni dei forni, della posizione dei bruciatori di riscaldamento, della fluido-dinamica dei fumi di riscaldamento, ecc, non si può

escludere che in alcune zone possano verificarsi temperature massime alquanto superiori a quella prescritta. Con queste premesse, non può essere escluso un effetto di sovra-rinvenimento non solo del cordone di saldature e della zona termicamente alterata, ma anche del metallo base; un rinvenimento eccessivo non solo produce una soluzione-riprecipitazione dei carburi, che aumentano la loro dimensione e sono in misura sempre maggiore posizionati al bordo grano, ma può anche favorire un aumento della dimensione dei grani di ferrite. Tutte queste modificazioni microstrutturali possono compromettere le proprietà di tenacità del metallo base, a causa del loro effetto dannoso sul comportamento alla frattura alle basse temperature.
Nel presente lavoro si sono effettuate prove di tenacità a frattura su un acciaio ASME SA-542/SA-542M sottoposto a condizioni di rinvenimento differenti per valutare l'effetto di temperature di trattamento superiori al livello massimo previsto per PWHT sia sulla microstruttura che sulla tenacità.

KEYWORDS. ASME SA542M steel; Post weld heat treatment; Base metal; Fracture toughness.

INTRODUCTION

In the last decade the operating conditions in the petrochemical industry have continuously shifted towards increased temperature and hydrogen pressure, and the ever stringent conditions call for new steels and welding consumables to satisfy more rigid requirements.

In the second part of the 90's, in addition to the conventional 2.25Cr1Mo standard low alloy ferritic steel, the V modified type, 2.25Cr1Mo0.25V steel started to be considered for manufacturing heavy wall reactors.

This new V modified steel was in fact introduced thanks to its capability to withstand the critical service conditions of petrochemical hydrogen pressurized processes and more elevated temperatures; concurrently, the new 2.25Cr1Mo0.25V steel was also introduced into the boiler and pressure vessels ASME code [1].

A lower sensitivity to the phenomenon of hydrogen embrittlement and a greater creep resistance, both in air and hydrogen environments, are the distinctive improvements of the low alloy V modified steel. Nevertheless, the most extolled advantages with respect to standard 2.25Cr1Mo are generally claimed to be the higher tensile properties at room and high temperature (450°C), that means a reduction in thickness and weight of heavy wall equipments.

Both standard and V modified low alloy ferritic steel in the course of the manufacturing process are necessarily (and repeatedly) subjected to different heat treatments [1], the aims of which are summarized as follows:

1. DHT (Dehydrogenation Treatment), carried out at 300–350 °C to reduce the hydrogen content in the weld metal to a level sufficiently low to prevent hydrogen cracking
2. ISR (Intermediate Stress Relieving), usually carried out at 620–650 °C to reduce residual stresses (and hydrogen) in the welded joints
3. PWHT (Post Weld Heat Treatment), carried out at 690°C for the standard steel or in the range 700–710 °C for the V modified steel, to modify the microstructure of both the weld metal and the heat affected zone, and to optimize the mechanical properties of the weldment.

Higher temperatures, up to 732 °C, are recommended by the American Petroleum Institute depending on which characteristic has to be favored [2].

Frequently in field welding operations have to be carried out either for fabrication or repairing purposes; as a consequence, a Post Weld Heat Treatment is required to stress relieve both the weld metal and the heat affected zone, and to decrease their hardness. This PWHT unavoidably results in a further tempering treatment also of the base metal, whose hardness and mechanical strength are further diminished. In addition, in field PWHT are not simple to carry out; heating panels are used, consisting of electrical resistances, embedded in ceramic tiles, under a proper insulation (Fig. 1). Notwithstanding each panel is controlled by a thermocouple, temperature may vary from zone to zone, and even under a single panel differences of +/- 5° C can be recorded. Furthermore, K type thermocouples that are usually used have an allowable max. error at the PWHT temperature of 0.5%.

Furthermore, also in the case of furnace treated components, considering the large size of the furnaces, the position of the heating burners, the fluido-dynamics of the heating fumes, etc., it cannot be excluded that some zones may experience a maximum temperature somewhat higher than the prescribed one.

Under these premises, over tempering of base metal may occur, resulting not only in a redistribution of carbides, which increase their size and are increasingly located at grain boundaries, but also in an increase of the ferrite grain size.

Since all these microstructural modifications are known to be detrimental [3-5] for the low temperature fracture behavior and may therefore modify the toughness properties of the base metal, in the present research work fracture toughness measurements have been carried out on an ASME SA-542/SA-542M steel subjected to different tempering conditions to assess the effect of treatment temperatures higher than the maximum level for PWHT on either microstructure and toughness.

Figure 1: Heating panels attached onto the lower part of a pressure vessel in correspondence of the circumferential weld to be PWH Treated (left); mineral insulating fibers shielding the whole zone to be heat treated (right)

EXPERIMENTAL PROCEDURES

A number of three point bend Charpy V type specimens have been machined out from a narrow gap weld either in the weld metal (WM) and in the heat affected zone (HAZ), as well as in the base metal (BM). The starting material is represented by a weld produced during the qualification procedure of the longitudinal weld for the manufacture of a heavy section reactor for the petrochemical industry, the base metal being a near 150 mm thick hot rolled plate.

The chemical composition of the BM plate, as well as the WM chemical composition are reported in Tab. I. The weld was obtained by manual SMAW technique with an interpass temperature of 200 °C min/250 °C max.

The qualification weld underwent the same heat treatments of the reactor, namely four Intermediate Stress Relievings (ISR) at 680 °C for 6 hours and one Post Weld Heat Treatment (PWHT) at 705 °C for 8 hours, hereafter referred to as the $\mathrm{PWHT_{min}}$ condition.

C	Mn	Si	Cr	Ni	Mo	V	S	P	Nb	Cu
Base metal (wt %)										
0.150	0.470	0.086	2.43	0.094	1.047	0.278	0.003	0.006	0.029	0.045
Weld metal (wt %)										
0.112	0.680	0.122	2.531	0.108	1.131	0.249	0.003	0.005	0.016	0.057

Table 1: Chemical composition of the base metal and weld metal of the weld coupon used for the mechanical tests. The content of low melting residuals, i.e. Sn, As, and Sb is well below the required limits for both the BM and WM.

A set of three WM and three HAZ Charpy V samples plus a 10x10 mm three point bend BM specimen ready to be pre-cracked have been subjected to an additional heat treatment at 710 °C; two further groups of specimens have been heat

treated at 745 °C and 780 °C respectively. The hold time for all the heat treatments has been of 30 min, according to the rule of thumbs that suggests a holding time of 1 h for each 25 mm (1 inch) of thickness.
The effect of an increase in the PWHT temperature on the fracture behavior of the WM and the HAZ has been evaluated by means of Charpy V impact test at – 29 °C, as prescribed by the applicable Standards.
The effect of an increase in the PWHT temperature on the fracture behavior of the BM has instead been assessed by means of fracture toughness tests on pre-cracked specimens at -29 °C.
For the BM the applicable Standard requires an impact test at the temperature of 0 °C; to assess the fracture behavior under more severe conditions, it was preferred to carry out the tests at a lower temperature and with a fatigue pre-crack instead of the Charpy V notch, to ensure a high degree of constraint at the crack tip and promote the transition towards the brittle behavior.

RESULTS AND DISCUSSION

Fig. 2 shows the load-load line displacement curves recorded during the three point bend test of the pre-cracked specimens; to allow a direct comparison of the load level independent of the different initial crack length a_0 of the specimens, the load L has been normalized as a function of the ligament size $b = W - a_0$, with W = specimen height. All the specimens show an elastic-plastic behavior with no sign of abrupt unloading, and a ductile fracture mechanism is therefore expected. From the general yield point on the curves L_{GY} and the geometric characteristics of the specimens the yield strength of the steel has been calculated by means of the relationship (1):

$$\sigma_{YS} = P_{GY}S/1.455Bb^2 \tag{1}$$

which is valid for plane strain conditions; S is the span in the three point bend fixture and B the specimen thickness. The following values have been obtained for the yield strength: 530 MPa for $PWHT_{min}$ (from the steel work certificate), 514 MPa for 710 °C, 505 MPa for 745 °C, and 492 MPa for 780 °C.
Fig. 3 shows the dependence of the yield strength on the Larson Miller Parameter (LMP). The LMP, which is a parameter often used [6-7] to expresses a quantitative equivalence between temperature and time of a thermally activated phenomenon, is given by:

$$LMP = T(20 + \log t)/1000 \tag{2}$$

where T is the temperature of the heat treatment (°K) and t the holding time (h) at maximum temperature.

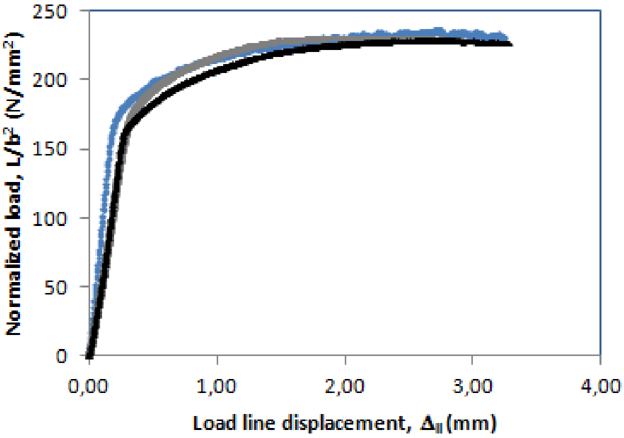

Figure 2: Normalized load vs. load line displacement curves; 1) 710 °C sample, 2) 745 °C sample, 3) 780 °C sample.

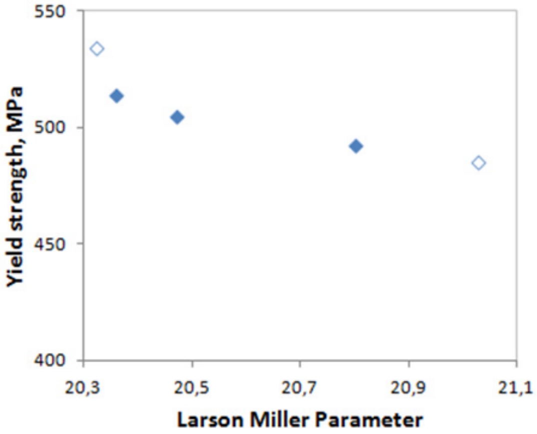

Figure 3: Base metal yield strength vs. Larson Miller Parameter; from left to right, closed points: samples additionally heat treated at 710, 745, and 780 °C respectively; open points: values from the steel work certificate for $PWHT_{min}$ and $PWHT_{max}$.

The effect of increasing the heat treatment temperature, as expected, is a decrease in yield strength; however, notwithstanding that at increasing the LMP the yield strength shows a continuous decrease, the strength level is still well higher than the minimum requested by the applicable standard, i.e. 415 MPa. In Fig. 3 the lowest yield strength corresponds to the PWHT$_{max}$ reported in the steel work certificate, i.e. 705 °C x 32 h.

The base metal HV$_{10}$ hardness as a function of the Larson Miller Parameter (LMP) is reported in Fig. 4.

From Fig. 4 it can be observed that, as for yield strength in Fig. 3, both temperature T and time t of the PWHT are effective in decreasing the hardness of the BM.

From both Figs. 3 and 4 it is also evident that the effect of the increased heat treatment temperature is in complete agreement with the conditions of PWHT$_{min}$ and PWHT$_{max}$, provided that the mutual effect of T and t are taken into account by means of the LMP.

The base metal fracture toughness (J$_{Ic}$) at – 29 °C as a function of the temperature of the additional heat treatment is shown in Fig. 5. At a first increase when the heat treatment temperature is increased from 710 to 745 °C, a small decrease is then observed for the highest heat treatment temperature. In order to understand the variation of the base metal fracture toughness of Fig. 5 it is first of all necessary to clarify that in all cases the fracture behavior has been ductile, with crack initiation and advancement by a micro-void nucleation and coalescence mechanism. Therefore the decrease observed for 780 °C treated specimen is not to be related to the onset of a transition towards brittle mechanisms of fracture.

The level of J$_{Ic}$ fracture toughness, at the onset of crack advancement, is primarily related to the energy dissipated at the crack tip, according to the yield properties of the steel matrix, either for blunting and for the achievement of maximum strain that the steel is apt to sustain.

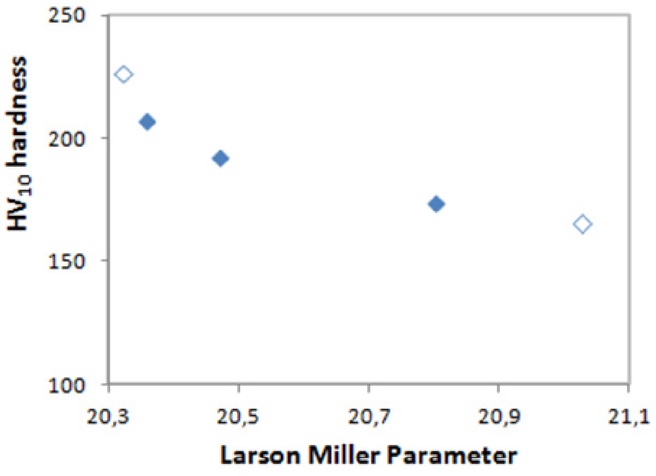

Figure 4: Base metal HV$_{10}$ hardness vs. Larson Miller Parameter; closed points, from left to right, samples additionally heat treated at 710, 745, and 780 °C respectively; open points, values from the steel work certificate for PWHT$_{min}$ and PWHT$_{max}$.

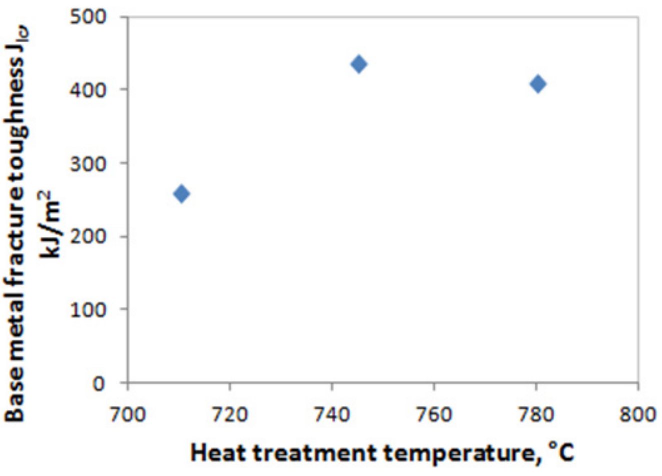

Figure 5: Base metal fracture toughness J$_{Ic}$ at – 29 °C vs. additional heat treatment temperature.

With regard to the yield strength the decrease observed at increasing the heat treatment temperature (Fig. 3) is to be ascribed to the small increase in grain size of the ferrite phase and to the solution and re-precipitation of carbides (Fig. 6, left side); the consequences of these microstructural modifications are larger mean free paths for dislocations and a decreased number of obstacles for their movements. The different yield properties of the metallic matrix control the development of the stress-strain field ahead of the crack tip, the increase of the plastic zone size, and the blunting of the crack tip and superimpose their effect to the nucleation of micro-voids, their coalescence.

A measure of the phenomena that precede crack initiation is well represented by the stretched zone width (SZW), which can measured by means of fractographic investigation (Fig. 6, right side), by pointing out the final advancement of the fatigue pre-crack (in the upper part of the pictures) and the crack propagation by micro-void nucleation and coalescence (in the lower part); a mean SZW of 110 μm, 190 μm, and 166 μm has been measured for samples additionally heat treated at 710, 745, and 780 °C respectively, with a direct correspondence with the measured J$_{Ic}$ levels.

Finally, the effect of treatment temperatures higher than the maximum level for PWHT on hardness and toughness has been also assessed for the WM and the HAZ.

Fig. 7 shows the relationship between hardness and LMP; as expected at increasing tempering time and temperature hardness shows a continuous decrease. As regards toughness, in the case of WM and HAZ Standards require a minimum notch toughness at -29 °C; all the Charpy V specimens, however, didn't fail totally under the maximum available impact energy of 300 J, so it can be concluded that no decrease in fracture toughness, nor a shift of the fracture transition towards low temperatures are caused by limited time heat treatments at temperatures higher than the maximum level prescribed for PWHT.

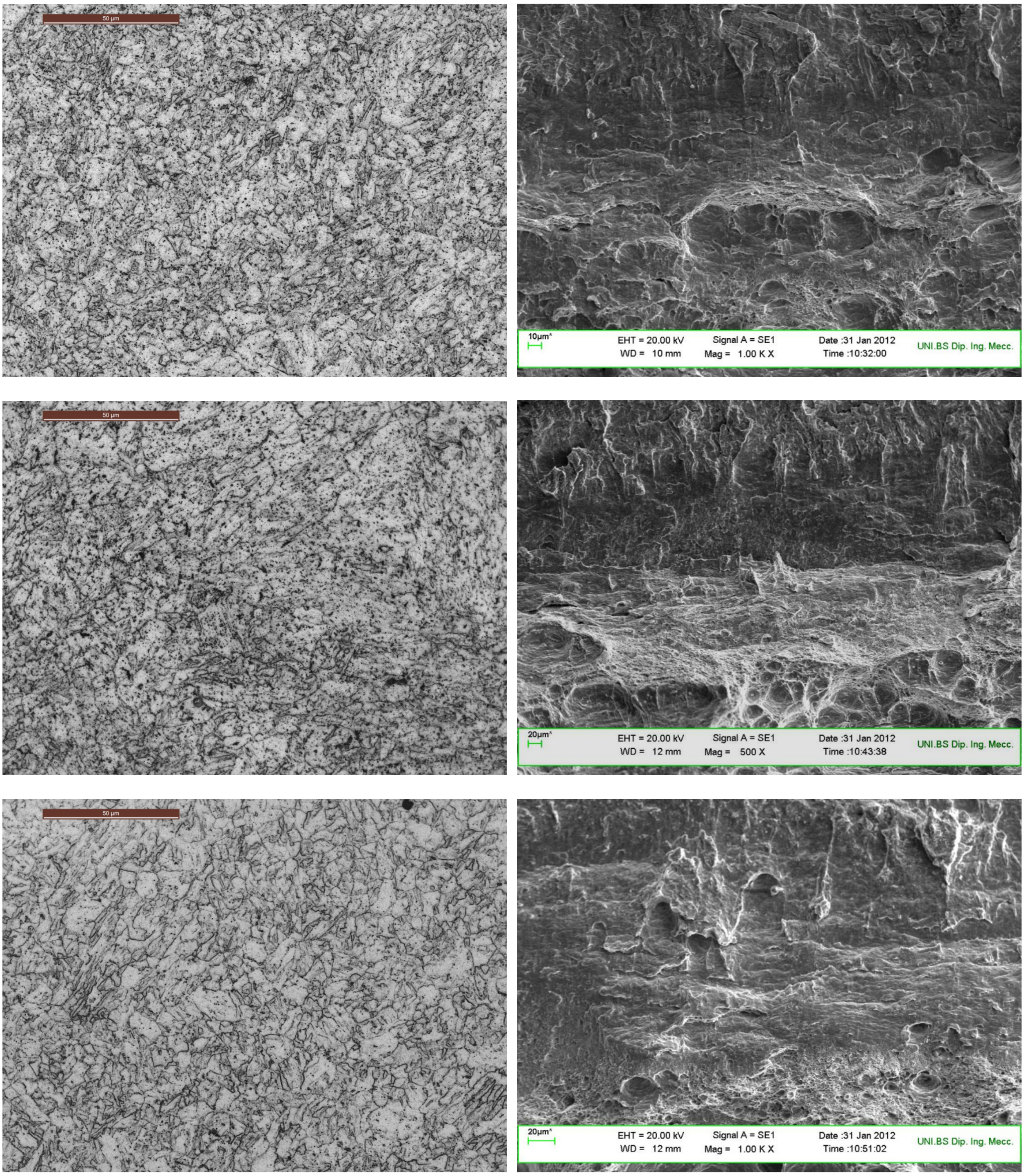

Figure 6: Base metal microstructure (left) after heat treatment at 710, 745, and 780 °C respectively and fracture appearance (right) of three point bending Charpy V type specimens heat treated at 710, 745, and 780 °C respectively and tested at – 29 °C

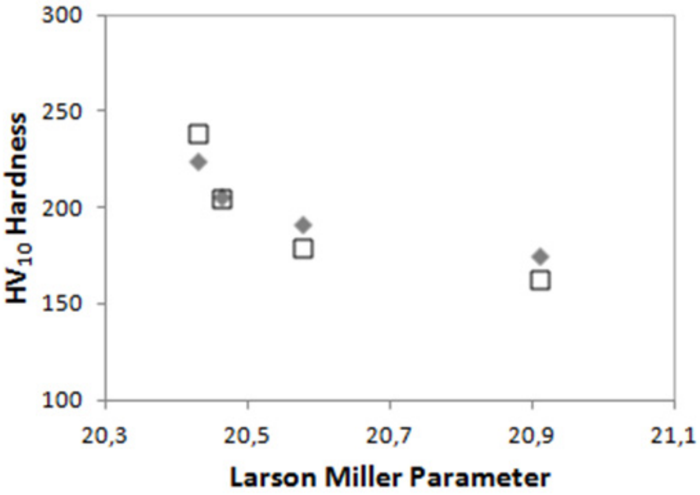

Figure 7: HV_{10} hardness vs. Larson Miller Parameter; closed point: weld metal, open point: HAZ.

CONCLUSIONS

Fracture toughness tests have demonstrated that heat treatments for a limited time at temperatures higher than the maximum level prescribed for PWHT cause only limited modifications in the microstructure and do not impair the fracture behavior of base metal, weld metal, and heat affected zone of ASME SA-542M pressure vessel steel.

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