Minería y Geología / v.31 n.2 / abril-junio / 2015 / p. 80-94 ISSN 1993 8012

Weldability examination of ASTM A 240 S41500 martensitic stainless steel by thermal cycles simulation testings

Alberto Velázquez-del Rosario
Armín Mariño-Pérez
Maritza Mariño-Cala

Abstract

The weldability assets of ASTM A 240 S41500 (ASTM A 240/A 240M) martensitic stainless steel are presented through the study of the effects of single and double thermal weld cycles on mechanical properties and microstructure of base metal and the artificial heat affected zone created by thermal weld simulations. For single cycles, separate peak temperatures of 1000 ºC/12 s and 1350 ºC/12 s (cooling times: 12 s in both cases) were evaluated, whilst two combinations of peak temperatures: (1 350 ºC/5 s + 1 000 ºC/5 s) ºC and (1 350 ºC/12 s + 1 000 ºC/12 s) ºC (cooling times: 5 s and 12 s), were applied for double cycles. Post weld heat treatment with short and long holding times were applied and Vickers hardness, impact toughness and metallographic examinations were used in order to assess mechanical and metallographic properties in the as-simulated (no heat treated) and postweld heat treated conditions. Best properties of the welded joint for double thermal weld cycles with long holding times were reached, which reveals the good weldability and applicability of the tested material in post weld heat treated conditions.

Keywords: martensitic steels; weldability; toughness; thermal weld cycles.

Recibido: 18 marzo 2015 Aprobado: 26 mayo 2015

Minería y Geología / v.31 n.2 / april-june / 2015 / p. 80-94 ISSN 1993 8012

Análisis de la soldabilidad del acero inoxidable martensítico a 240 s41500 mediante ensayos de simulación de ciclos térmicos

Resumen

Se presentan resultados de análisis de la soldabilidad del acero inoxidable martensítico ASTM A 240 S41500 (ASTM A 240/A 240M) a partir del estudio de los efectos de ciclos térmicos de soldadura, sencillos y dobles, sobre las propiedades mecánicas y la microestructura del metal base y una zona afectada por el calor creada artificialmente mediante simulaciones térmicas de soldadura. Para los ciclos simples se evaluaron picos de temperaturas de 1 000 ºC/12 s y 1 350 ºC/12 s (tiempos de enfriamiento: 12 s en ambos casos), por separado, mientras que para los ciclos dobles se aplicaron dos combinaciones de picos de temperaturas:(1 350 ºC/5 s + 1 000 ºC/5 s) ºC y (1 350 ºC/12 s + 1 000 ºC/12 s) ºC (tiempos de enfriamiento: 5 s y 12 s). Se aplicaron tratamientos térmicos pos-soldadura (TTPS) con tiempos de corta y larga duración y se realizaron ensayos de dureza Vickers, impacto y metalográfico, con el objetivo de determinar las propiedades mecánicas y metalográficas en condiciones de no simulación (sin tratamiento térmico) y con tratamientos térmicos pos-soldadura. Las mejores propiedades de la unión soldada se obtuvieron en los ciclos térmicos de soldadura dobles con elevados tiempos de permanencia, lo que revela la buena soldabilidad y aplicabilidad del material ensayado en condiciones de tratamientos térmicos pos-soldadura.

Palabras clave: aceros martensíticos; soldabilidad; tenacidad; ciclos térmicos de soldadura.

Received: 18 march 2015 Accepted: 26 may 2015

1. INTRODUCTION

Martensitic stainless steels have been used traditionally for a wide range of applications, mainly due to their balanced properties, as they couple relatively microhardness, mechanical resistance and corrosion resistance in many aggressive environments (Krauss 2005; Marin, Lanzutti & Fedrizzi 2013). So, they are widely used for pipelines, pressure vessels and downhole tubulars for oil and gas production in aggressive environments at elevated temperatures, typically up to about 125 ºC or so, but due to the carbon content problems for welding make the steel unsuitable for transmission lines (Marin, Lanzutti & Fedrizzi 2013).

Carbon steels with inhibitors has been used traditionally for pipelines but the cost of maintenance is a disadvantage. To achieve a balance of capital and maintenance costs in distributing fluids which are not too aggressive, 13 Cr steels with very low carbon content, ≤ 0,02 %, were developed, with a range of Ni and Mo contents designed to give varying degrees of corrosion resistance according to the service conditions (Marin, Lanzutti & Fedrizzi 2013).

Lower carbon content likewise improves welding properties, gives improved resistance to pitting and general corrosion as a consequence of reduced carbides (Cr23C6) formation and associated Cr depletion (Xi, Liu & Han 2008).

Felton and Schofield, cited by Turnbull and Griffiths (2002), suggest three categories of martensitic stainless steels: standard 13 Cr (e.g. 420), lower carbon 13 Cr (e.g. 410) and alloyed supermartensitic steels with very low carbon and with Mo and Ni additions. In principle, the low C content enables the pipe to be welded satisfactorily, without post weld heat treatment (McGuire 2008). Corrosion resistance is considered to be improved by the addition of Ni, but Felton and Scholfield in reported work by Turnbull and Griffiths (2002) suggest that low Ni contents can be detrimental, whilst high contents (4 %-5 %) are beneficial.

Ni, being an austenite stabilizing element, is used to obtain a fully austenitic material during hot working and then a fully martensitic material without any delta ferrite phase, addition of elements such as Mn and Cu aids the austenite formation, whilst Cr and Si promote lower ferrite formation. Likewise, the addition of Mo improves pitting resistance and enhances passivity (Calliari *et al.* 2008).

Very low carbon martensitic stainless steel have been developed for general services because they offer a good compromise between high strength, toughness and corrosion resistance, associated to satisfactory weldability (Miyata *et al*. 1997; Xi, Liu & Han 2008). After welding, post weld heat treatment (PWHT) is usually performed to improve mechanical properties. That's why they have been limited and successfully used in pipes, tubes, pressure-containing and tubing services for hydraulic applications (Krauss 2005).

The review of selected literature (Miyata *et al.* 1997; Alphonsa *et al.* 2002; Turnbull and Griffiths 2002; Corengia *et al.* 2004; Sobiecki, Mankowski & Patejuk 2004; Li and Bell 2006; McGuire 2008; Xi, Liu & Han 2008; Brühl *et al.* 2009; López, Tschiptschin & Alonso 2009; Casteletti *et al.* 2010; Liu and Yan 2010; Ferreno *et al.* 2011; Isfahany, Saghafian & Borhani 2011; Butt and Tabish 2013; Marin, Lanzutti & Fedrizzi 2013) revealed that even when the range of materials suppliers has been increased markedly and the steels have been adopted in a wide number of applications, investigations emphasizes, mainly, on the knowledge and understanding of the behaviour of conventional high and medium carbon martensitic stainless steels with attendant issues from a corrosion perspective, environment assisted cracking, stresses in service and/or improvement of strength and wear resistances.

The present investigation focuses on the weldability examination of S41500 very low carbon, chromium nickel molybdenum martensitic stainless steel by weld and PWHT simulation testing. The BM and HAZ properties of the material were investigated in order to determine the properties distribution in the zones affected at various temperatures and to offer a perspective about the influence of holding time for PWHT in the weldability of very low carbon medium alloy martensitic stainless steels.

2. EXPERIMENTATIONS

Standard full size Charpy V-notch specimens (Type A) were prepared according to ASTM E23 from a 10 mm sheet of ASTM A 240 S41500 (ASTM A 240/A 240M) martensitic stainless steel with average chemical composition (wt. %): C = 0,014; Cr = 12,550; Ni = 4,820; Mo = 1,480; Mn = 1,05; Si = 0,360; P = 0,022; S = 0,0030; Cu = 0,220; Al = 0,001; N = 0,0118; Fe = balance).

The temperature history for single and double thermal cycles was simulated in SMITWELD TSC 1405 machine, with a distance between electrodes of 15 mm.

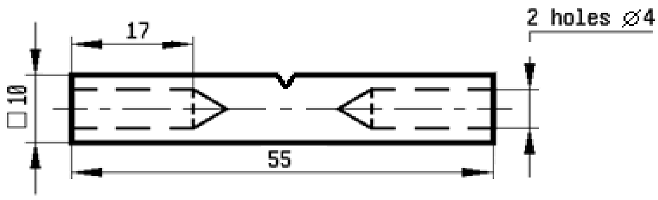

Figure 1. Main dimensions of specimens

For high cooling rate water injection method was employed in center holes drilled in the specimens, as shown in Figure 1. The specimens were heated and cooled according to parameters listed in Table 1.

Table 1. Set parameters for single and double thermal cycle simulations

Cycles	Set Parameters		
	Peak temperatures (ºC)	**Heating rate (ºC/s)**	**Cooling times (s)**
Single	1000	90	12
	1350		
Double	1350 + 1000		5/5
			12/12

After weld simulations, the samples were heat treated at different temperatures, as shown in Table 2. The PWHT consisted in tempering for short (5 min) and long (30 min) holding times.

Table 2. Set parameters for post weld heat treatments

Kind of simulation (temperature/cooling time)	**Set parameters for PWHT**	
	Temperature, (°C)	**Holding time, (min)**
Base Metal	580	5
	600	5
	620	5
		30
Simple simulated, 1000 °C/12 s	580	5
	600	5
	620	5
		30
Simple simulated, 1350 °C/12 s	580	5
	600	5
	620	5
		30
Double simulated, (1350 + 1000) °C/5 s	580	5
	620	30
Double simulated, (1350 + 1000) °C/12 s	580	5
	620	30

Short times were obtained at SMITWELD machine with heating rate of 10 ºC/s, and for long times an electrical furnace was used with heating rate of 150 ºC for 1 h.

Vickers hardness and toughness testing were conducted in order to evaluate mechanical properties for BM and artificial HAZ under different conditions of welding and PWHT. Vickers indentations were practiced with an applied load of 10 kgf during 10 s (HV10/10 scale) on calibrated MITUTOYO MVK-H1equipment, according to ASTM E-92, whereas toughness examinations were practiced using Charpy-V notch (CVN) method in an HOYTOM, J300 model machine, according to ASTM E-23.

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Three indentations were made for each test condition and thus the average values of the multiple tests were taken as the final results and reported in this paper.

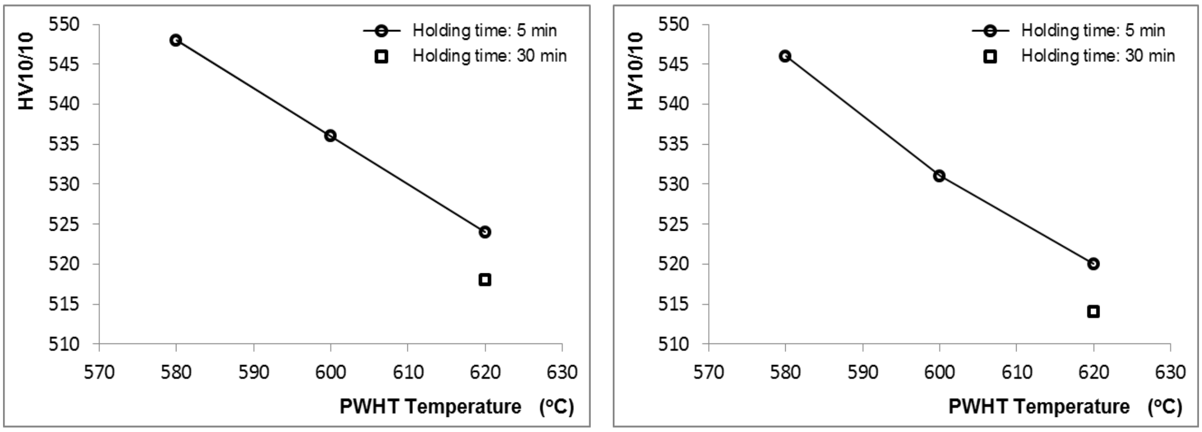
In this way, two sets of replicate samples were separated: one set of specimens was used for Charpy-V notch tests and the other set of specimens was used for hardness measurements and for optical microscopy analysis.

OLIMPUS AX70 light optical microscope equipped with a CCD digital camera was used to characterize the as-quenched and tempered microstructures. Before microscopy, the samples were grinded and polished down to 6 μm using diamond paste and etched with Villella etchant, according to ASTM E3-01.

3. RESULTS AND DISCUSSIONS

3.1. Hardness measurements

Figure 2 and 3 describes how the average hardness values of the HAZ changed with PWHT temperature and holding time for simple and double cycle simulated samples, whereas for the test material in as-received condition, the average hardness was HV = 322. The maximum error percentages for each average hardness value were calculated and did not exceed 2,38 % what can be accepted as satisfactory.



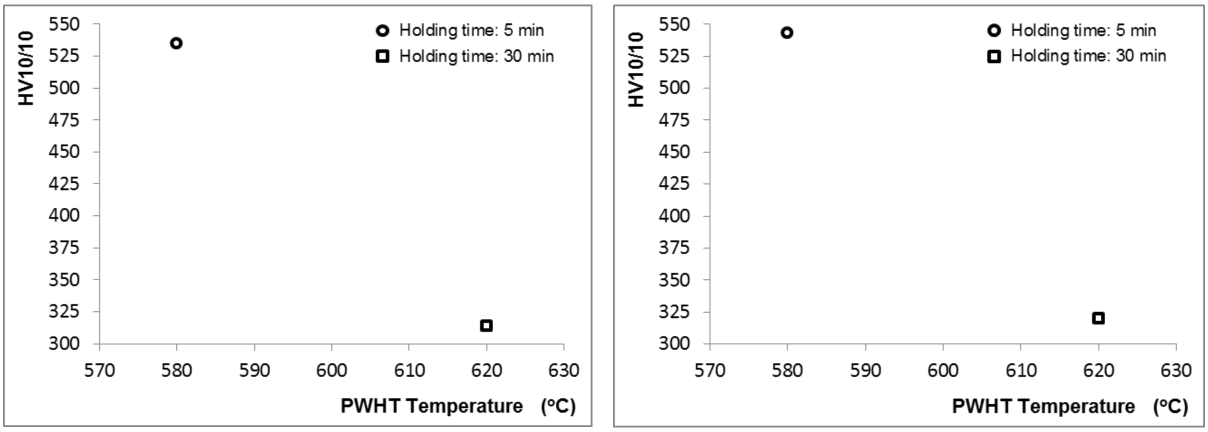
a) b)

Figure 2**.** Variation of hardness for HAZ in simple cycle. a) 1000 °C/12 s; b) 1350 °C/12 s

According to Figures 2 a, b, while temperature was increased in simple cycle, the hardness values underwent, even when discreet values, similar decreasing law (a- from 548 HV down to 524 HV and b- from 546 HV) for 5 min of holding time. Single points show, as well, very close hardness values (518 HV and 514 HV respectively), which correspond to

30 min of holding time. In this case, insignificant difference among hardness values for 1000 ºC and 1350 ºC peak temperatures were achieved and, even when the largest softening effect was after 30 min of holding time at 620 ºC for both peak temperatures, such hardness values may be considered still high if compared with initial hardness of BM (HV = 322).

In simulations done with double cycle (Figure 3 a, b) for both: 5 s and 12 s of cooling times, high hardness values (535 HV and 543 HV respectively) were kept when PWHT were conducted at 580 ºC and short holding time (5 min).



a) b)

Figure 3. Variation of hardness for HAZ in double cycle. a) (1350 + 1000) ºC/5; b) (1350 + 1000) ºC/12 s.

In contrast to hardness described for 5 min of holding time, significantly diminished hardness values (314 HV and 320 HV respectively) were reached for both: 5 s and 12 s cooling times when PWHT were conducted at higher temperature (620 ºC) and longer holding time (30 min).

The softener effect of higher temperature and holding time may be considered as satisfactory in the sense that hardness values close to the initial hardness of BM were reached.

3.2. Charpy V-Notch measurements

The behavior of toughness under different conditions of welding and PWHT, is shown in Figures 4 and 5. Toughness tests provided initial toughness value of 117 J for BM in as-received condition, and the variation of toughness for BM after different temperatures of PWHT and holding times is represented in Figure 4.

In this case, short holding times (5 min) increased slightly the toughness value up to 120 J when the BM was tempered at 580 ºC and 620 ºC and the highest softener effect (CVN = 125 J) was reached when the BM was tempered at 600 ºC.

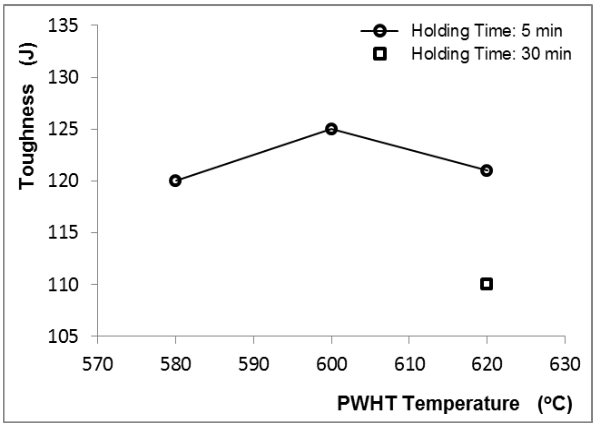
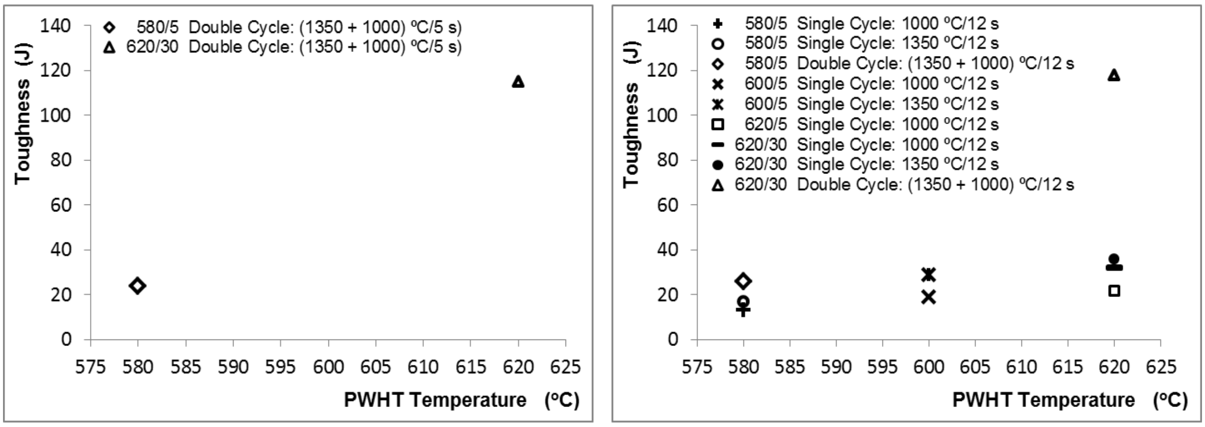


Figure 4. Variation of toughness for BM after different PWHT and holding times

But even when longer holding times of tempering (30 min) at 620 ºC worsened slightly the toughness (CVN = 110 J). These results prove that BM toughness values can be considered as satisfactory and, independently of holding times, tempering does not affect the toughness of BM.

The plots in Figure 5 describe how the toughness for the HAZ varied with peak temperature, holding and cooling times for single and double cycles. Simulations done with double cycles with 5 s of cooling time (Figure 5a) reported a toughness behavior completely different for the two investigated temperatures and holding times.



a) b)

Figure 5. Variation of toughness of HAZ for: a) Double cycle and 5 s of cooling time; b) Single and double cycles and 12 s of cooling time

Samples tempered at 580 °C and 5 min of holding time, reported very low values of toughness (24 J), but when the temperature and holding time of PWHT were increased (620 °C and 30 min respectively), then the toughness was enhanced significantly and satisfactory value (115 J) was reached, very close to the initial toughness value for BM.

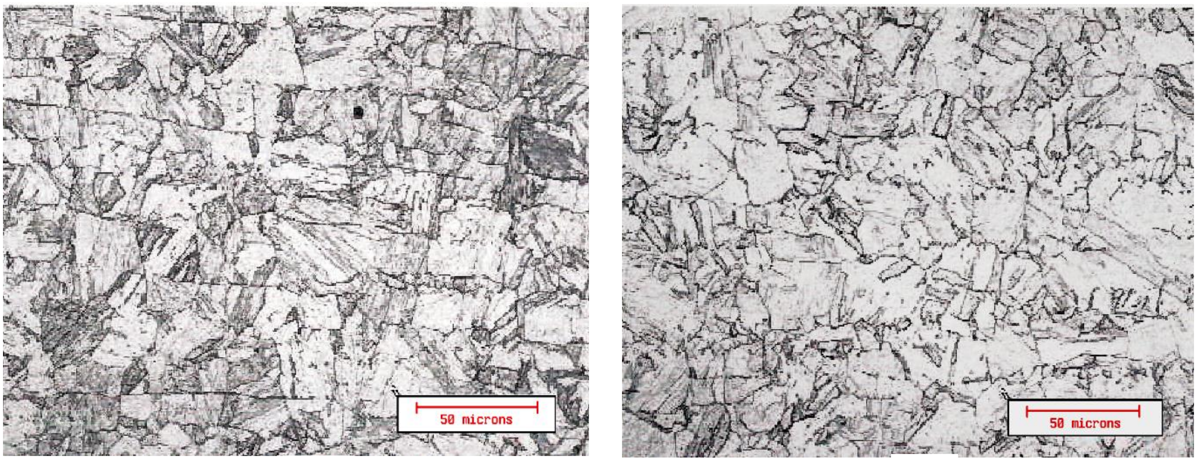
In the case of simple and double cycles, but with 12 s of cooling time (Figure 5b), the best value of toughness (118 J) corresponds only to PWHT at 620 ºC and 30 min of holding time, very close to the initial toughness value for BM. The other values, with the respective minimum and maximum values of: 13 J and 26 J at 580 ºC, 19 J and 29 J at 600 ºC and 22 J and 36 J at 620 ºC are considered unsatisfactory. Even when long holding times (30 min) were also applied to post weld heat treated samples at 620 ºC for single cycle, the toughness could not be improved too much.

On the contrary to single cycle at high temperatures and long holding time, the positive effect of double cycle at high temperatures and long holding time were put in evidence for softening the HAZ and to promote satisfactory weldability of welded UNS S41500 martensitic stainless steels.

3.3. Metallographic examinations

Photomicrograph from Figures 6 and 7 illustrate the typical microstructure of BM in as-received and PWHT conditions, respectively.

The initial microstructure of the BM (Figure 6) is mainly martensite lathes in low quantities on an austenitic matrix, which explains the good hardness and toughness values associated to as-received metal and tested formerly. Once the BM was heat treated, even for several conditions of temperature and holding times, the microstructure was kept mainly also of austenite matrix coexisting with martensite lathes in low quantities, as shown in the representative microstructure from Figure 7.



a) b)

Figure 6. Typical microstructure for BM. a) In as-received condition, b) Postweld heat treated at 620 ºC. Magnification: 200 x

It must be emphasized, further, that when comparing morphology of grains from Figure 6, deformation treads can be observed on grain boundaries in the direction where, presumably, the grains became geometrically constrained during plastic deformation of parent metal. For the magnification used (200 x) martensitic lathes could be revealed only because of their existence in large sizes.

Figure 7 shows the microstructure of specimens simulated in single cycles (1 000 °C/12 s and 1 350 °C/12, tempered at 5 min and 30 min of holding times) and double cycle: (1 350 + 1 000) °C/5 with 5 s and 12 s of cooling time, but with short holding times, while Figure 8 corresponds to microstructure of simulated HAZ for double cycle simulated samples at (1 350 + 1 000) °C/5, 5 s and 12 s of cooling time, 30 min of holding times.

Figure 7. Typical microstructure of simulated HAZ for specimens thermally cycled

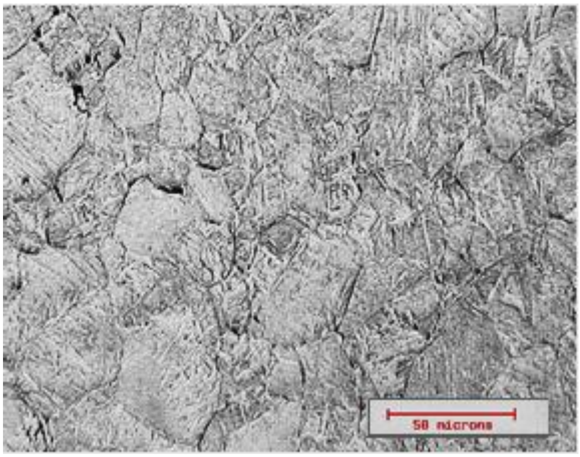


Figure 8. Typical microstructure of simulated HAZ for specimens thermally cycled in double cycle, 5 s and 12 s of cooling time, 30 min of holding times

In Fgure 7, big quantities of small martensite laths coexisting with low concentration of remaining austenite were observed, but only for higher magnifications. This microstructure matches up, undeniably, with the corresponding hardness and toughness values described in Figures 2 and 5 for the corresponding PWHT condition. In such cases, the high hardness and toughness values are associated to the predominance of small martensite lathes above the few quantities of remaining austenite.

Finally, as can be seen in Figure 8, the double cycle simulated samples at (1 350 + 1 000) °C/5 with 5 s and 12 s of cooling time but for 30 min of holding times, showed a microstructure with constituents of martensite lathes in low quantities on an austenitic matrix, similarly to microstructure of BM from Figures 6 and 7. In this case, and such as in the preceding analysis, this microstructure matches up, as well, with the corresponding hardness and toughness values described in Figures 3 and 5 for each PWHT condition.

In general, if linking results from hardness and toughness tests versus metallographic examinations, several regularities may be mentioned: 1) the absence of microcracks; 2) the satisfactory correspondence among hardness and toughness values with metallographic microstructures, result that agrees with Calliari (2008) and López, Tschiptschin & Alonso (2009); 3) the low hardness and toughness values experimented for different conditions of PWHT, are in accordance with the prevalence of small martensite laths coexisting with low concentration of retained austenite, result that agrees with Turnbull and Griffiths (2002); López, Tschiptschin & Alonso (2009); Yang, Yu & Wang (2006) and Butt and Tabish (2013); 4) the good hardness and toughness values tested for BM in as-received and after PWHT conditions, as well as for simulated HAZ in double cycle and PWHT with long holding time, are in accordance with the prevalence of big quantity of remaining austenite above low quantities of big martensite lathes 5) when little deterioration of hardness and toughness are observed, the transformation of retained austenite at higher temperatures possibly could be the reason (Krauss 2005; McGuire 2008; Calliari 2008; López, Tschiptschin & Alonso 2009; Isfahany, Saghafian & Borhani 2011) and 6) it is to expect that increasing the holding time at higher values than 30 min, the rest of remaining austenite could be transformed and the toughness will be improved.

4. CONCLUSIONS

1. The positive effect of high temperatures and long holding times for softening the HAZ of welded ASTM A 240 S41500 (ASTM A 240/A 240M) martensitic stainless steel were put in evidence in the present investigation.

2. Best results were reached for PWHT of double cycle with cooling time of 5 and 12 s and long holding time due to good metallurgical conditions of microstructure, composed mainly for retained austenite and minimum quantities of martensite laths with very good combination of hardness and toughness values, according to standard specifications.

3. Weldability of tested ASTM A 240 S41500 (ASTM A 240/A 240M) martensitic stainless steel can be classified as acceptable but under double cycle and long holding time postweld heat treatment conditions, in view of good hardness values and metallurgical characteristics taken by the HAZ and the of absence of defects like microcracks.

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Alberto Velázquez del Rosario. avelazquez@ismm.edu.cu
Doctor en Ciencias Técnicas. Profesor Titular.
Departamento de Ingeniería Mecánica.Facultad de Metalurgia y Electromecánica.
Instituto Superior Minero Metalúrgico. Moa, Holguín, Cuba.

Armín Mariño Pérez. amarino@ismm.edu.cu
Doctor en Ciencias Técnicas. Profesor Titular.
Departamento de Ingeniería Mecánica. Facultad de Metalurgia y Electromecánica.
Instituto Superior Minero Metalúrgico. Moa, Holguín, Cuba.

Maritza Mariño Cala. marino@fim.uo.edu.cu
Doctora en Ciencias Técnicas. Profesoa Titular.
Departamento de Manufactura y Materiales.
Facultad de Ingeniería Mecánica, Universidad de Oriente, Santiago de Cuba, Cuba.