JMEPEG (2009) 18:324–331
DOI: 10.1007/s11665-008-9294-5

Evaluation of AISI 4140 Steel Repair Without Post-Weld Heat Treatment

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(Submitted October 15, 2007; in revised form May 30, 2008)

The present work evaluates the two-layer technique on the heat affected zone (HAZ) of AISI 4140 steel welded with different heat input levels between the first and second layer. The weld heat input levels selected by the Higuchi test were 5/5, 5/10, and 15/5 kJ/cm. The evaluation of the refining and/or tempering of the coarsened grain HAZ of the first layer was carried out using metallographic tests, microhardness measurements, and the Charpy-V impact test. The tempering of the first layer was only reached when the weld heat input ratio was 5/5 kJ/cm. The results of the Charpy-V impact test showed that the two-layer technique was efficient, from the point of view of toughness, since the toughness values reached were greater than the base metal for all weld heat input ratios applied. The results obtained indicate that the best performance of the two-layer deposition technique was for the weld heat input ratio 5/5 kJ/cm employing low heat input.

Keywords AISI 4140 steel, hardness, Higuchi test, toughness, two-layer, welding

1. Introduction

C-Mn and low alloy steels are widely used for parts and equipment in the chemical, petrochemical, and oil and gas industries (Ref 1). These steel parts and equipment are employed in harsh working environments, causing component wear and even equipment failure. Repairs that involve welding procedures should take into account some aspects of the weldability of these materials. In general, the main negative effects caused by welding of these steels to be avoided are excessive grain growth and the formation of non-tempered martensite with a high level of hardness in the heat affected zone (HAZ), which when associated with the presence of hydrogen and tensile residual stresses can cause cold cracking (Ref 2-5).

C-Mn and low alloy steels, such as AISI 4130, 4140, 4340, and 1045, generally have a carbon content of around 0.4% and carbon equivalent (CE) values between 0.6 and 0.9, which according to the literature (Ref 6) are highly susceptible to cracking, and these steels require care in the choice of the filler metal and welding parameters. Also, they need preheating, interpass temperature control, and the use of post-weld heat treatments (PWHT) (Ref 4, 7).

The use of preheating and interpass temperature control in the 250-300 °C range is required for repairs with these steels to control the cooling velocity so it is slow enough to avoid cold cracking induced by hydrogen. PWHT is carried out immediately after welding to reduce the high hardness levels of HAZ, to relieve the welding residual stresses, and to eliminate hydrogen present in the weld metal and in the HAZ. This is necessary in view of the fact that the high hardness and the coarse grains of HAZ, associated with the presence of stresses, are again favorable conditions for the formation of cold cracking induced by hydrogen.

Although PWHT may bring benefits to the weld joint, it has drawbacks such as long equipment downtime, high costs, or even impracticability for field repairs. Consequently, welding procedures that do not require PWHT have an advantage in terms of time and cost. This need to bypass PWHT has stimulated research for new techniques that promote refining and tempering of HAZ during welding.

Among the main techniques developed along these lines are the half bead and the two-layer techniques. In the half-bead technique, the top half of the weld bead is ground off after every pass before applying the next layer, which promotes the tempering of the previous HAZ layer (Ref 8-11).

The two-layer technique, as with the half-bead technique, requires the deposition of two layers of weld so that the heat generated during the second layer weld is sufficient to promote refining and tempering of the first layer coarsened grain heat affected zone (CGHAZ), reducing the hardness and increasing the toughness (Ref 12). This technique, which was initially developed to prevent reheating cracks, has been successfully applied to welding procedures for low alloy steels without PWHT (Ref 13-25). There are two important disadvantages of the half-bead technique compared to the two-layer technique: (i) the removal of the first layer by grinding makes this repair technique slow and uneconomical and (ii) difficulty to control the grinding off depth (Ref 10).

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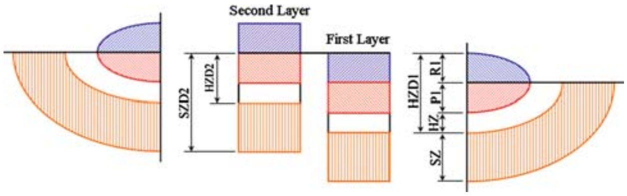

Fig. 1 Superimposition of layers in the Higuchi test

In the two-layer technique, the correct choice of the welding heat input applied in the first and second layers is a primary factor for its success. The Higuchi tests (Ref 26) have proven to be an important tool to choose the correct weld heat input ratios (Fig. 1). The test consists of obeying two conditions:

$$\text{(a)}\quad \mathrm{SZD2} > \mathrm{HZD1}: \Delta 1 = \mathrm{SZD2} - \mathrm{HZD1}; \quad (+)\,\text{Comply.}\ (-)\,\text{Not Comply.} \qquad \text{(Eq 1)}$$

where SZD2 is the softened zone depth of the second layer and HZD1 is the hardened zone depth of the first layer.

$$\text{(b)}\quad \mathrm{HZD2} < \mathrm{R1} + \mathrm{P1}: \Delta 2 = (\mathrm{R1} + \mathrm{P1}) - \mathrm{HZD2}; \quad (+)\,\text{Comply.}\ (-)\,\text{Not Comply} \qquad \text{(Eq 2)}$$

where HZD2 is the hardened zone depth of the second layer, R1 the weld face reinforcement of the first layer, and P1 is the weld penetration of the first layer.

Complying with the first condition means that the heat contained in HAZ of the second layer refines the CGHAZ and tempers the hard zone (HZ) of the first layer, while complying with the second condition guarantees that the HZ of the first layer will not be re-quenched. In this case, the melted zone of the first layer will be austenitized, proportioning a recrystallization and the formation of some martensite that due to the low carbon content does not present high levels of hardness. Although the Higuchi tests produce good results for tempering of HAZ, the same cannot be said for grain refining. Often, an inadequate degree of refining and tempering in the regions between passes occurs, making these regions into localized brittle zones (LBZ), consequently reducing the efficiency of the technique.

The aim of the present work is to evaluate the success of the two-layer technique with AISI 4140 steel, without PWHT, in terms of optimization of the microstructure, hardness, and toughness of the HAZ and compare the results with welded joints under the same conditions but submitted to PWHT. One of the main focuses is given to the possible formation of LBZ.

2. Materials and Methods

The tests were carried out on ϕ150 × 25 mm AISI 4140 steel disks extracted from hot laminated ϕ150 mm bars with chemical composition shown in Table 1. The filler material used was an AWS E8018 B2 covered electrode with a 2.5 and 3.25 mm diameter. The chemical composition of the filler metal according to the manufacturer is shown in Table 1. Petrobras technicians recommended this electrode since it is the one used for weld repairs with AISI 4140 steel.

The methodology developed was carried out in two stages: the Higuchi test, for which the welds were executed in an Automatic Positioner for Experimental Welds with Covered Electrode, developed by *Laboratório de Engenharia de Soldagem* (Weld Engineering Laboratory) at the Federal University of Ceará, and the tests with the Semi-V joints that were executed by a qualified welder. Both stages are addressed below.

Table 1 Chemical composition of the base and filler metal (wt.%)

	C	Mn	Si	P	S	Cr	Mo
Base metal	0.45	0.86	0.29	0.03	0.006	1.1	0.23
Filler metal	0.08	0.90	0.60	…	…	1.0	0.5

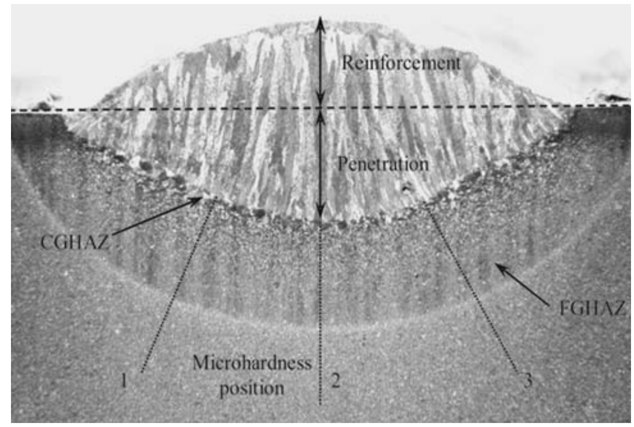

Fig. 2 Identification of weld regions and location of the hardness measurements

2.1 Higuchi Test (1st Stage)

In this stage, single bead welds were carried out on quenched test samples (austenitized at 860 °C in a salt bath for 20 min and cooled in oil), as shown in Fig. 2. Four different welding heat input levels were tested as shown in Table 2. After which, the microhardness profiles were taken in three directions of HAZ, following the lines 1, 2, and 3 with an approximate angle of 30° (Fig. 3), to obtain the average hardness along the HAZ extension and determine the extension of the HZ and soft zones (SZ) for each welding heat input applied. The average hardness of the base metal used for the Higuchi test was 550 HV; this value was used to determine the HZ and SZ. The load employed in the microhardness test was 100 g and the distance between impressions was 0.2 mm. The reinforcement and the penetration of the weld beads were measured using an optic microscope, with an amplification of 25×. The Higuchi graph was built-up on the reinforcement, penetration, and extension results of the HZ and SZ.

2.2 Test with Semi-V Joint (2nd Stage)

In order to evaluate the success of the two-layer deposition welding procedures, six semi-V joints were welded in a quenched (austenitized at 860 °C in a salt bath for 20 min and cooled in oil) and tempered (200 °C for 1 h) AISI 4140 steel. Two semi-V joints were welded for each welding condition, as shown in Fig. 3. The buttering of the bevel faces with two layers was carried out with a heat input ratio from the Higuchi test. The buttering weld parameters are shown in Table 3.

Table 2 Welding parameters of AISI 4140 steel

Sample	Current, A	Tension, V	Welding speed, cm/min	Welding heat input, kJ/cm
HC5	103	27	30	5.5
HC10	101	26	15	10.5
HC15	102	26	10	15.9
HC20	117	26	10	18.2

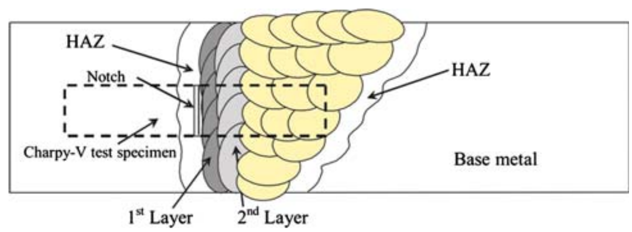

Fig. 3 The deposition sequence

Table 3 Buttering welding parameters

Heat input ratio	Layer	Current, A	Tension, V	Welding speed, cm/min	Welding heat input, kJ/cm
Semi-V 5/5	1st	102	27	30	5.3
	2nd	103	27	30	5.4
Semi-V 5/10	1st	100	27	30	5.2
	2nd	102	26	15	10.6
Semi-V 15/5	1st	103	26	10	15.7
	2nd	103	27	30	5.4

The lateral passes in the first layer could also act in the partial refining of the HAZ as well as in the tempering. Aloraier and his collaborators (Ref 27, 28) confirmed that an overlay varying between 50 and 70% could be beneficial for the HAZ, improving the microstructure and the hardness. Consequently, an overlay of 50% between the layers was attempted to guarantee an additional grain refining and tempering via the lateral passes.

After the buttering, the joint filling was carried out according to the weld parameters shown in Table 4. During the welding, the temperature of preheating and interpass was maintained between 250 and 300 °C, values recommended by Bueno (Ref 19).

After the welding, a test sample for each condition underwent a PWHT at a temperature of 600 °C for a period of 4 h and the other sample remained in its as-welded state. The samples were prepared and evaluated using metallographic examination with an optic microscope and a scanning electronic microscope, microhardness tests following the ABNT NBR NM 188-1 (Ref 29) standard specifications and also the Charpy-V impact test that was carried out following the ABNT NBR 6157 (Ref 30) standard. The notch in the test specimen was placed in the coarse grain HAZ.

Two criteria were established to evaluate the success of the two-layer deposition technique applied in this work. The first is that the hardness of the HAZ should not exceed 300 HV and the second is that the toughness should be better than or equal to the base metal.

Table 4 Welding parameters for filling of semi-V joint

Parameters	Root pass	Filler pass
Current, A	70	109
Tension, V	22	23
Welding speed, cm/min	20	Welder's decision
Preheating temperature, °C	250-300	250-300
Interpass temperature, °C	250-300	250-300
Electrode diameter, mm	2.5	3.25

3. Results and Discussion

3.1 Higuchi Test

The micrographic analysis of the base metal in the quenched and non-tempered conditions indicated the presence of bright bands along the lamination. This defect is known as banding and is due to a lack of homogeneity of the chemical composition of the steel (Ref 31). An EDX chemical composition analysis of the two bands revealed a variation in the Cr content. The bright band presented 1.2% Cr while the dark band had only 0.9%. This localized variation in chemical composition causes alterations in the hardenability between the bands. Although it is not possible to determine the C content using EDX analysis, it is possible that the alterations of the Cr content could produce variations in the C percentage between the bands, due to strong Cr and C affinity. Microhardness tests were carried out in the bright and dark bands, giving hardness values of 885 ± 64 HV for the bright bands, which were much greater than the average values of the dark bands of 658 ± 38 HV, indicating a greater hardenability in the light colored bands and probably a greater C content than in the dark band. These bands can be a critical region for welding.

Figure 4 presents the microhardness profiles of the traverse sections of the test samples for each weld heat input, acquired from the connecting zone and extending through to the HAZ and base metal as indicated in Fig. 2. In the HAZ region, there is high hardness adjacent to the weld bead, with values of around 750 HV, so that this region is known as the HZ. Following it can be seen that that there is a drop in the hardness values, caused by tempering of the microstructure proportioned by the welding heat inputs. This region is known as the SZ, which should overlie the regions of high hardness in two-layer welding.

From these graphs it is possible to determine the extension of the hard (re-quenched) and soft (tempered) zones. Figure 4 shows how the increase of weld heat input increases the size of the HZ. The SZ also follows the same behavior as the HZ, growing in relation to weld heat input. The reinforcement and penetration evaluations of the weld beads show distinct behaviors for each region as the weld heat input increases. Note that the weld reinforcement grew as the weld heat input applied grew. As to penetration, there was no variation in relation to the increase of weld heat input. The extension of HZ and SZ, together with the values of reinforcement and average penetration, is presented in Table 5.

The Higuchi graph was built-up based on the values presented in Table 5 (Fig. 5). In these graphs, the acceptance or non-acceptance of the criteria established by Higuchi (Ref 26) is confirmed in Eq 1 and 2. In the analysis of the first condition (Eq 1), the positive values of Δ1 are considered satisfactory, since they indicate that SZD2 is greater than HZD1, confirming

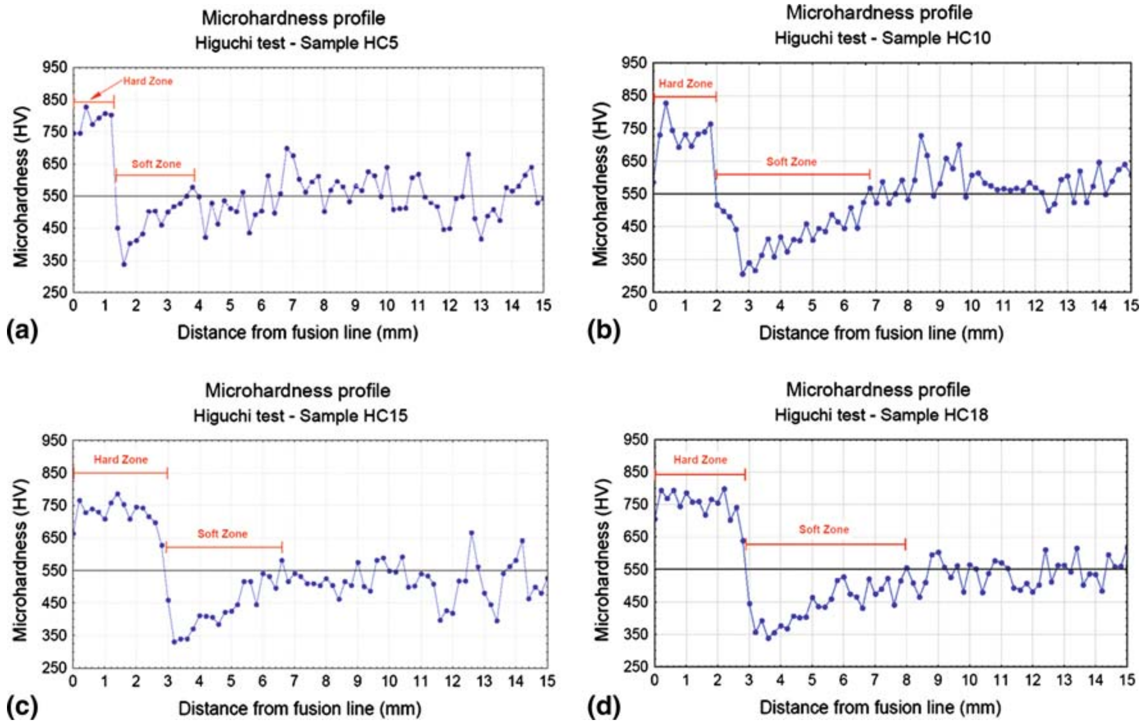

Fig. 4 Microhardness test sample profiles of AISI 4140 steel: (a) 5 kJ/cm, (b) 10 kJ/cm, (c) 15 kJ/cm, and (d) 20 kJ/cm

Table 5 Extension values (mm) of various regions of the weld for the Higuchi test of ABNT 4140 steel

Sample	Welding heat input, kJ/cm	R	P	HZ	SZ	HZD	HZD	SZD	R + P
HC5	5	1.2	1.5	1.2	1.8	3.9	2.7	4.5	2.7
HC10	10	2.2	1.5	1.8	5.2	5.5	3.3	8.5	3.7
HC15	15	2.5	1.1	2.8	3.2	6.4	3.9	7.1	3.6
HC18	18	3.1	1.6	2.8	4.0	7.6	4.4	8.4	4.7

Note: R, reinforcement; P, penetration; HZ, depth of hard zone; SZ, depth of soft zone; HZD, depth of hard zone of the first layer; HZD, depth of hard zone of the second layer; SZD, depth of the soft zone of the second layer

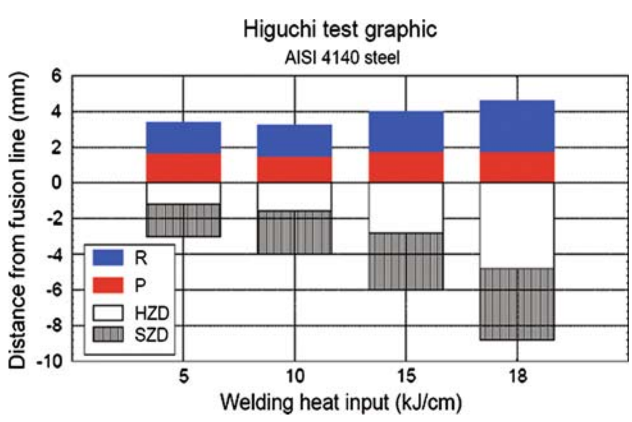

Fig. 5 The Higuchi graph

that this first condition was reached for almost all the heat input ratios except for the 10/5, 15/5, 18/5, and 18/15 ratios. These rejected conditions have high weld heat input in the first layer in common, which makes the tempering difficult in the HZ of the first layer by applying a second layer. Besides this, although the Higuchi test did not take into consideration the microstructural alterations, the use of high energies in the first layer provokes a high grain growth, also making the refining of CGHAZ difficult on applying the second layer.

The compliance with the second condition (Eq 2) is considered satisfactory when values of $\Delta 2$ are greater or equal to 0 and unsatisfactory for negative values. Positive values indicate that the HZ of the second layer would be contained within the weld metal which, because it has a low C content, will produce a martensite with low hardness and therefore not become a critical region. On the other hand, negative values indicate a re-quenching of the HAZ of the first layer, creating a region of high hardness.

Not all the weld heat input ratios complied with this condition. Analyzing the results it can be seen that the weld heat input ratios with low heat output in the first layer, such as 5 kJ/cm, did not produce good results when the heat input of the second layer was three to four times greater than the first. To weld with 5 kJ/cm in the first layer, the second layer weld heat input should be two times the first, guaranteeing a value very close to 0, indicating that this heat input level can still be applied.

Almost all the weld heat input ratios turned down one of the conditions when welding with 10 or 15 kJ/cm in the first layer, the exception being for the ratios 10/10 and 15/10. When the maximum weld heat input is applied in the first layer (18 kJ/cm), all the weld heat input ratios are satisfied for the second condition (Eq 2). However, it should be pointed out again that this weld heat input ratio does not comply with the first condition of the criteria from Higuchi and promotes an intense grain growth.

In the present work, the following weld heat input ratios between the first and second layer were chosen: 5/5, 5/10, and 15/5. The first two were recommendations from the literature (Ref 15) that indicates weld heat input in the second layer up to two times the first. However, according to the Higuchi test, the ratio 5/10 presented a negative value of $\Delta 2$, which indicates that this ratio does not comply with the second condition, since it could generate some re-quenching. However, this condition was selected since it presented a $\Delta 2$ value very close to 0 and a lower heat input in the first layer. Of the ratios that presented $\Delta 1$ close to or less than 0 (10/5, 15/5, 18/5, and 18/15), 15/5 ($\Delta 1 = -2.0$ mm) was selected. This ratio was selected because it presented a heat input level much greater in the first layer than in the second, which results in an intense grain growth in the CGHAZ of the first layer, causing great difficulty for grain refining and tempering of martensite on applying the second layer.

3.2 Two-Layer Deposition

Figure 6(a) shows various regions of the HAZ along the plane face of the semi-V joints for the weld heat input ratio 5/5 kJ/cm without PWHT. The presence of coarse microstructures can be seen that were not sufficiently refined as the other regions (point A), presenting a hardness of 387 HV. On the other hand, the other regions of HAZ were tempered and refined satisfactorily, presenting hardnesses in the range of 248-257 HV (points B and C). Also, the region on the extreme right of the semi-V bevel (point D) was not completely refined, but presented a hardness of 267 HV, compatible with the tempered and/or refined regions.

Figure 6(b) shows the microstructure along the whole extension of the HAZ for the weld sample with a weld heat input ratio of 5/5 kJ/cm and submitted to PWHT. In general, the samples welded with this weld heat input ratio (5/5 kJ/cm), with and without PWHT, presented the best degree of refining, with very few regions having coarse microstructures (points A and D), as shown in Fig. 6(a) and (b). The hardnesses of these regions was also satisfactory, presenting values close to 260 HV for point A and 219 HV for points B and C.

The samples welded with the heat input ratio 5/10 kJ/cm, with and without PWHT, presented very similar results from the refining point of view. Point A on the extreme left had the same value of hardness for the sample with and without PWHT (284 HV). The hardness values at the point B region were 214 and 218 HV for the samples with and without treatment, respectively. In the C region, the degree of refining was almost as effective as those for the samples welded with the 5/5 kJ/cm heat input ratio. The hardness values also did not vary between the samples with and without PWHT, being 218 HV for the sample without and 221 for the sample with PWHT. Also, on the extreme right the degree of grain refining was good, presenting a small region with coarse granulation. The hardness was 268 HV for the sample without and 273 HV for the sample with PWHT.

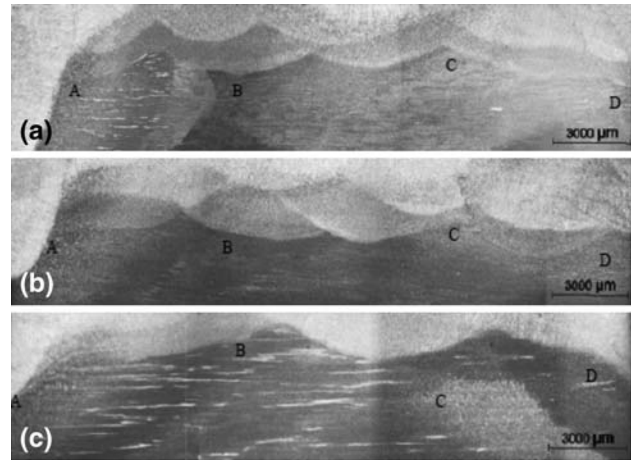

Fig. 6 Extension of the HAZ: (a) 5/5 kJ/cm without PWHT, (b) 5/5 kJ/cm with PWHT, and (c) 15/5 kJ/cm without PWHT

The weld sample with the heat input ratio of 15/5 kJ/cm without PWHT presented regions partially refined (point A), but with a satisfactory level of refining, presenting hardness values of 279 HV, as shown in Fig. 6(c). Also, like point A, point C in Fig. 6(c) shows the presence of partially refined regions, containing low hardness of around 260 HV. Point B was made up of regions that presented complete refining and tempering of the microstructure with hardness values around 250 HV. To the extreme right of the joints, higher hardness values (268 HV) and a degree of unsatisfactory refining presenting coarse microstructure were noted.

The microstructures of all the regions indicated in Fig. 6, evaluated by scanning electronic microscope, are shown in Fig. 7. For the ratio 5/5 kJ/cm, the formation of large grains of bainite above point A can be seen, together with the presence of tempered martensite plates (Fig. 7a and b). At point B where an intense grain refining was seen, there is a presence of martensite and ferrite grains with carbides. The microstructure of point C was made up of only tempered martensite.

For the weld 15/5 kJ/cm heat input ratio between the first and the second layer without PWHT, there is an inefficient refining of grounds. Only at point B are there small grains, the other regions (A, C, and D) have a microstructure with coarse granulation. This result was expected when using a much higher value in the first layer than in the second and confirmed the difficulty of refining the CGHAZ of the first layer with the heat input of the second layer.

The presence of bright bands along the HAZ of the weld sample with a weld heat input ratio of 15/5 kJ/cm without PWHT was investigated by SEM. The point A indicated that these bright bands become dark when analyzed by electron microscopy. In Fig. 7(c), the bright bands (dark in SEM) are made up of martensite. Also, it can be noted that the dark bands (bright bands in SEM) are made up of a mixture of upper bainite and martensite. Analyzing the interior of the martensite blocks in the bright bands (dark in the SEM analysis) in detail needles of lower bainite (Fig. 7d) may be seen. At point B, which was the region that presented an effective grain refining, martensite and ferrite were present. Point C shows that it is made up of upper bainite grains and tempered martensite, both with coarse granulation.

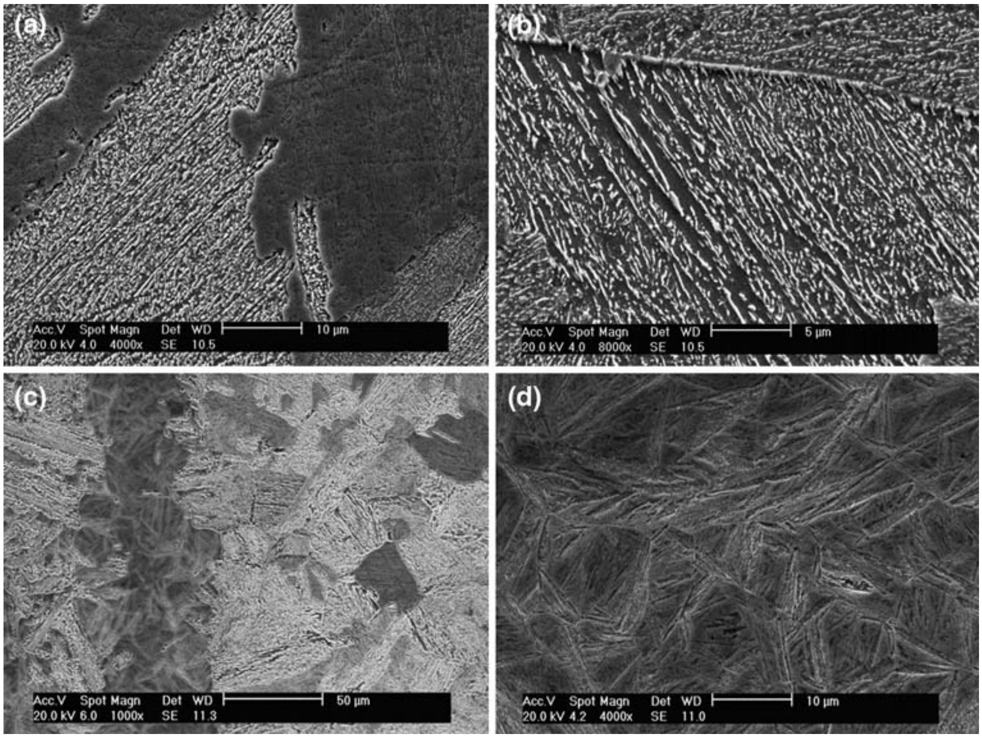

Fig. 7 SEM of the HAZ regions: (a, b) sample welded with 5/5 kJ/cm and submitted to PWHT; (c, d) sample welded with 15/5 kJ/cm and submitted to PWHT

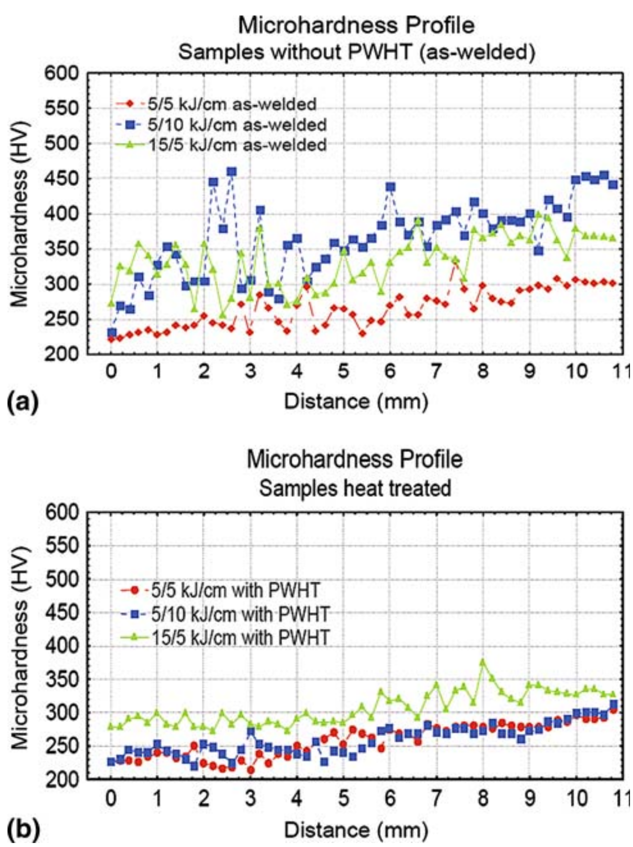

Fig. 8 Microhardness profiles of test samples welded with two-layer deposition: (a) without PWHT and (b) underwent PWHT

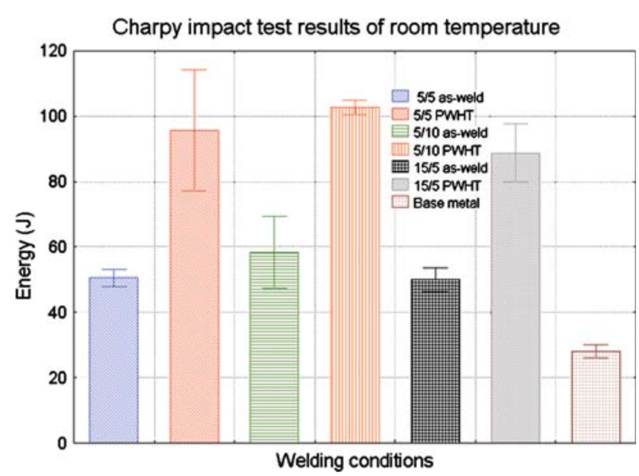

Fig. 9 Result of the Charpy-V impact test for samples

In the sample with the same heat input ratio (15/5 kJ/cm) and submitted to PWHT, the levels of hardness presented values close to those obtained in the sample without PWHT. The main microstructural changes in the samples heat treated were the most tempering effect on the martensite, resulting in a decrease of hardness and a reduction of the banding that contribute to get better homogeneity of the chemical composition. At the extremities of the joint, the average values were 270 and 259 HV (points A and D, respectively). The regions indicated by the points B and C presented hardness values of 230 and 234 HV, respectively.

From the microhardness profile surveys it can be seen that the softening of the HZ of the first layer due to the perfect match with the second layer took place for all situations, as can be seen in Fig. 8(a). For the tests samples that underwent PWHT, Fig. 8(b) shows the treatment proportioned a greater reduction of hardness and a better uniformity along the HAZ, compared to the test samples welded with a two-layer deposition without PWHT. According to the hardness acceptance criteria established in the methodology, only the heat input ratio 5/5 kJ/cm was able to reduce the hardness of the HAZ to below 300 HV. Whereas PWHT was able to reduce the hardness in all welding conditions evaluated.

The results of the Charpy-V impact test presented a significant variation in terms of energy absorbed between the test samples with and without PWHT (Fig. 9). The samples that underwent PWHT absorbed a greater level of energy than the samples in the as-welded state (without PWHT). The criteria for toughness were considered satisfactory for all the conditions of heat input applied in this work since toughness levels greater than the base metal were reached.

Evaluating the fracture surface of the Charpy test samples a homogeneous behavior in the area of the brittle fracture (center of the fracture) is seen for the samples submitted to PWHT. The same behavior was not observed in samples without the treatment. There were bands along the surface of the fracture in the region of the brittle fracture. SEM showed the presence of dimples, characteristics of a ductile fracture. These bands/dimples are intercalated (on the fracture surface) with cleavage facets, indicating a process of brittle fracture.

It is important to point out that this behavior observed in the samples without PWHT, probably due to the presence of banding, was not a critical defect, since the two-layer deposition welded samples without PWHT obtained energy levels in the Charpy-V impact test similar to the values reported in literature for the 4140 steel in the quenched and tempered condition (40 J) (Ref 32) and were therefore considered satisfactory.

4. Conclusion

Based on the experimental results obtained for the welding conditions used in this work, it was possible to conclude that:

- The efficiency of the two-layer deposition technique was approved for AISI 4140 steel with the weld heat input ratio 5/5 kJ/cm, since the hardness of the HAZ test sample without PWHT was reduced to values less than 300 HV and similar to the test samples submitted to PWHT.
- In the regions between the passes and extremities of the joint, there were regions with coarse granulation but without high levels of hardness; however, they could represent critical regions known as LBZ.
- In the hardness profile survey to make the Higuchi graph, the presence of hard bands aligned in the direction of the lamination should be considered.
- The results of the Charpy-V impact test showed that the two-layer deposition technique was efficient, from the point of view of toughness, since all the weld heat input ratios applied were capable of reaching toughness values greater than the base metal.
- The results obtained indicate that the best performance for the two-layer deposition technique was for the weld heat input ratio 5/5 kJ/cm applying low heat output.

Acknowledgments

The authors thank the laboratories ENGESOLDA and LACAM of UFC and LEM of CEFET-CE for their laboratory support. They also thank Petrobras for their support in the research and the development agencies (CNPq, FINEP, and ANP/PRH-31) for financial support.

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