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Effect of nonmetallic inclusion and banding on the success of the two-layer temper bead welding technique

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ABSTRACT

This work evaluated the effect of banding and nonmetallic inclusions in AISI 4140 steel on the HAZ toughness using the two-layer temper bead technique. The results showed that the amount and the length of the nonmetallic inclusions can negatively influence the toughness. There was a significant difference between the toughness of the materials with banding in the as-welded state and the heat treated. In conclusion, the two-layer temper bead welding technique can be used satisfactorily in welding without PWHT for AISI 4140 steel. However, a close evaluation of the base metal characteristics is decisive for the success of the repair technique.

1. Introduction

The use of maintenance welding for various steels is a very common practice in industry. For steels that present good hardenability, welding is critical due to the formation of non-tempered martensite in the heat affected zone (HAZ), which associated to intense grain growth makes this region even more fragile. Consequently, certain welding procedures for C–Mn and low alloy steels must be followed to avoid problems such as cold cracking and guarantee adequate mechanical properties, mainly toughness [1,2]. Among the procedures recommended are the use of low-hydrogen electrodes, the use of preheating, control of the interpass temperature and post-weld heat treatment (PWHT) [3,4].

However, PWHT is often impractical since it may not be possible to take the piece to the furnace or there is a possibility of damaging components beside the area to be welded. Also the costs may be too high. The need to bypass PWHT has motivated research and development into new repair techniques capable of promoting the refining and tempering of HAZ during welding.

Among the different welding techniques without PWHT that have been studied and developed in recent years is the two-layer temper bead welding technique which has gained a certain prominence. This technique was initially developed to avoid reheating cracks, but at present it is being applied with success to determine welding procedures for low alloy steels without PWHT [5–10].

In this technique, two layers of weld are deposited in such a way that the heat generated during the second layer deposition is sufficient to promote refining and tempering of the coarse grain heat affected zone (CGHAZ) of the first layer thereby reducing the hardness and increasing the toughness. This two-layer technique does not require removal of half of the first layer as in the case of the half-bead technique [11], and is therefore very interesting from an economic point of view.

Despite the advances in welding procedures without PWHT, the success of the two-layer temper bead welding technique in terms of mechanical properties can be affected by the base metal quality. Aguiar [12], in his work on the two-layer temper bead welding technique in welding AISI 4140 steels without PWHT, attributed the low levels of energy absorbed in the Charpy impact test to the presence of elongated inclusions of MnS with excessive length and in large quantities. He also observed the presence of bands rich in Cr and C, which after quenching became extremely hard. These two types of defects could induce a low level of toughness to the base metal when welding repairs are carried out, compromising the performance of the technique. The present work evaluates the effect of banding and nonmetallic inclusions in AISI 4140 steels concerning the toughness of the HAZ using the two-layer temper bead welding technique.

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2. Materials and methods

The work was carried out using AISI 4140 steel disks as the base metal with a ∅150 × 25 mm extracted from hot laminated bars from two different factories, named Lots C and W with their respective chemical compositions shown in Table 1. The filler metal used was a AWS E8018 B2 covered electrode with diameters of 2.5 and 3.25 mm. The chemical composition of the filler metal, according to the manufacture, is shown in Table 2. This electrode was suggested by Petrobras technicians since it is the one used by Petrobras for welding repairs of AISI 4140 steel.

The microstructural characteristics of the base metals were evaluated and correlated with the welding results. The two-layer deposition welding procedures were applied on six semi-V joints of 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 for each heat input relation (X/Y (kJ/cm) – X = heat input of the 1st layer; Y = heat input of the 2nd layer), as shown in Fig. 1. The buttering of the bevel faces in the two layers was carried out with heat input relations chosen from the Higuchi test, the results of which can be found in the work of Silva et al. [13]. The buttering weld parameters are shown in Table 3. The lateral passes in the first layer could also act in the partial refining of the HAZ as well as in tempering. The filling of the joint was carried out in accordance with the welding parameters found in Table 4. During the welding, the preheating and interpass temperatures were maintained between 250 °C and 300 °C, following the recommendations from the literature [14].

After welding, the test samples were divided into two equal parts one of which was submitted to post-weld heat treatment at a temperature of 600 °C for a period of 4 h and the other was left in its as-welded state. The evaluation consisted of preparing the samples for metallographic tests with optical and scanning electron microscopes; hardness tests following the ABNT NBR NM 188-1 standard specifications and Charpy-V impact tests which were carried out following the standard ABNT NBR 6157. The position of the notch in the Charpy-V test samples was located in the CGHAZ of the 1st layer, which was refined and tempered by the 2nd layer, approximately 1 mm from partial melted zone, as indicated in Fig. 1.

Table 1
Chemical composition of the base metals (wt%)

Lot	C	Mn	Si	P	S	Cr	Mo
W	0.42	0.86	0.27	0.03	0.021	1.10	0.21
C	0.45	0.90	0.30	0.03	0.006	1.00	0.25

Table 2
Chemical composition of the filler metal (wt%)

C	Mn	Si	Cr	Mo
0.08	0.90	0.60	1.00	0.50

Table 3
Welding parameters of the double layer deposition

Lot	Sample	Layer	Current (A)	Tension (V)	Welding speed (cm/min)	Welding heat input (kJ/cm)
W	Semi-V 5/5	1st	102	26	30	5.3
		2nd	99	25	30	4.9
	Semi-V 5/10	1st	103	25	30	5.0
		2nd	100	25	15	9.8
	Semi-V 15/5	1st	99	25	10	14.8
		2nd	99	25	30	4.9
C	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

Table 4
Welding parameters for buttering in semi-V joints

Parameters	Root pass	Filler pass
Current (A)	70	109
Tension (V)	22	23
Welding speed (cm/min)	20	Welder criterion
Preheating temperature (°C)	250 and 300	250 and 300
Interpass temperature (°C)	250 and 300	250 and 300
Electrode diameter (mm)	2.5	3.25

3. Results and discussion

3.1. Evaluation of the inclusions

There was a significant difference between the two base metals evaluated in relation to the nonmetallic inclusions, especially MnS. Lot W presented a greater percentage and greater lengths of these inclusions as shown by the results of the quantitative evaluation of the inclusions via image analysis in Table 5. The chemical composition analyses of the base metals show that Lot W has almost four times more sulfur content than Lot C, although both are within the standard limits (Table 1). Inclusions with lengths greater than

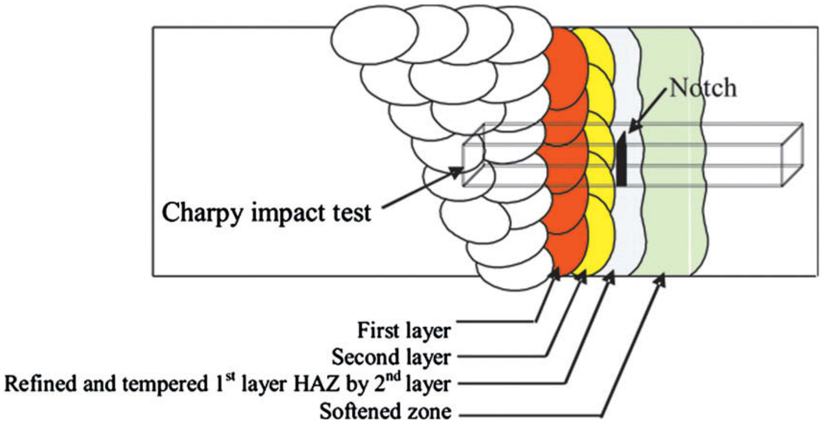

Fig. 1. Schematic drawing of the semi-V joint showing the two layers and the position of the Charpy impact test.

Table 5
Nonmetallic inclusions evaluation

Lot	Mean percentage	Standard deviation	Length (μm)	Standard deviation
W	2.1	0.7	250	198
C	0.2	0.1	16	12

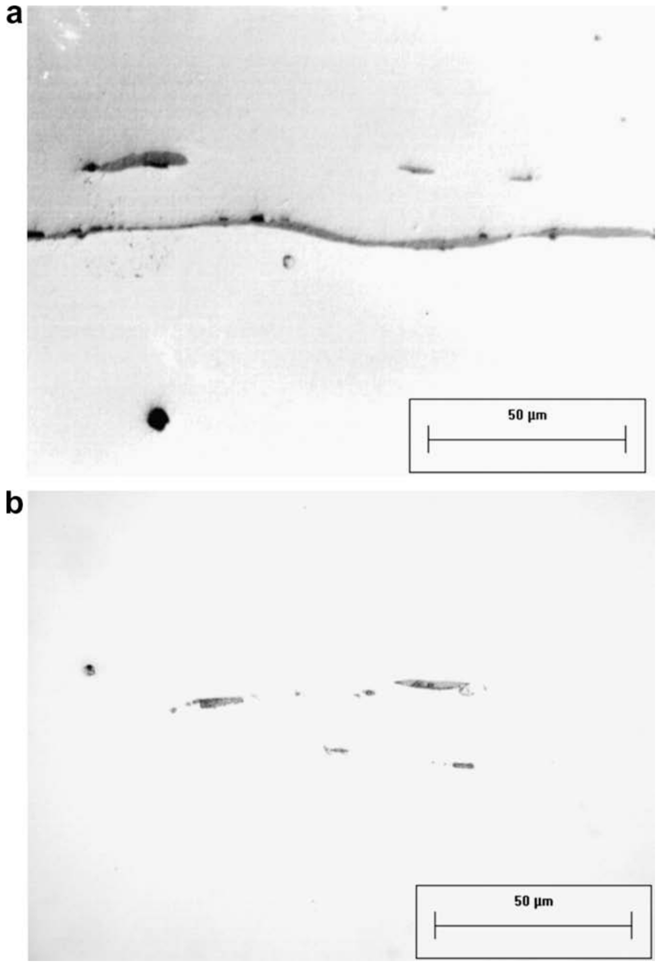

Fig. 2. Comparison between the size of the MnS in the AISI 4140 steels: (a) Lot W and (b) Lot C.

500 μm were observed in Lot W. Fig. 2a shows a micrograph of a sample from Lot W without metallographic etching. A long MnS inclusion can be seen traversing the whole photograph. Also it should be pointed out that the full length of the inclusion was not totally within the field of the image. Another important observation was a major concentration of inclusions in the central region of the bar, which can be justified by the greater segregation of residual elements in this region of the bar during solidification.

The second lot, Lot C, was much ‘cleaner’ compared to Lot W, since the percentage and the length of the nonmetallic inclusions were much less, as shown in Fig. 2b. The results of the quantitative analysis are presented in Table 5, where the percentage of inclusions in Lot C is around 10 times less than for Lot W.

3.2. Evaluation of banding

In both the base metal samples the presence of bright and dark bands along the laminations (Fig. 3a and b) was observed. The bands which are known as banding are formed due to the segregation of the alloy elements during the manufacturing process. In the particular case of the 4140 steel (Lot C) according to the chemical analysis carried out by EDX, the concentration of Cr in the bright bands was around 1.2%, while in the dark bands the Cr content was 0.9%. There was no significant difference for the Mo content and the C content cannot be determined by EDX. However, in the literature it is reported that during chromium segregation it is possible that carbon is also segregated to the richest chrome bands, due to the affinity of these two elements. This implies that during the austenitizing process, followed by rapid cooling, the bands rich in alloy elements will produce a greater quantity of martensite due to the greater hardenability proportioned by the alloy elements and greater hardness since there is a greater percentage of carbon in this region.

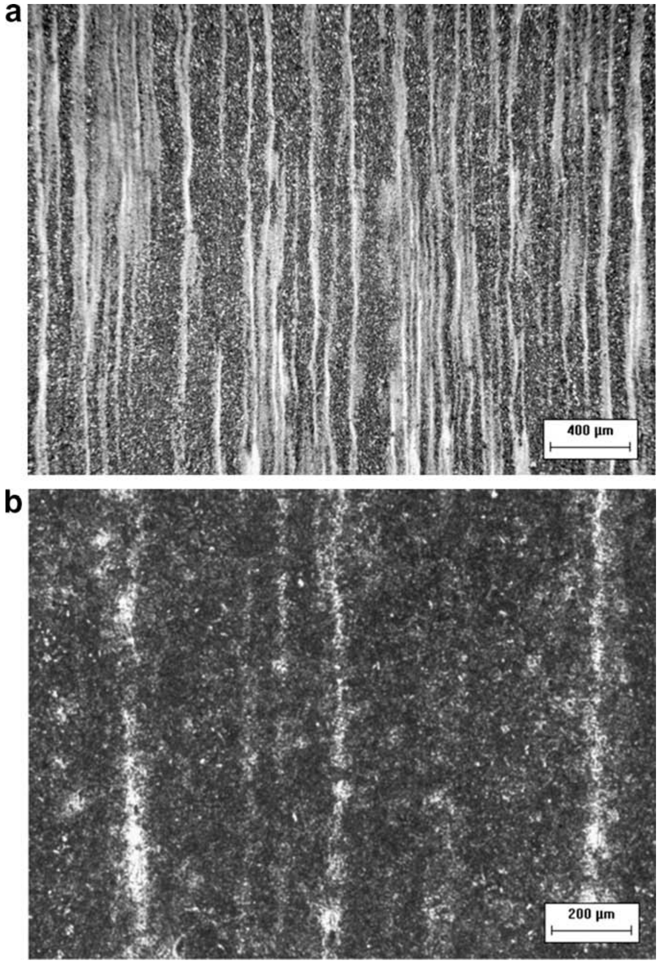

Fig. 3. Microstructure of the AISI 4140 steel, quenched and tempered: (a) Lot C. Presence of bright bands formed by martensite with high hardness and rich in chrome. Etching: Nital 2%. Enlarged: 25× and (b) Lot W. Presence of few bright bands. Etching: Nital 2%. Enlarged: 50×.

Table 6
Hardness values of the bright and dark bands

Lot	Hardness (HV)	
	Bright band	Dark band
C	885 ± 64	658 ± 35
W	577 ± 20	526 ± 19

Due to the segregation, a significant difference of hardness was confirmed between the bright and the dark bands as shown in Table 6. The average hardness of the bright streak (rich in Cr and C) for the base metal of Lot C was ~885 HV, about 200 HV greater than the average hardness of the dark streak (658 HV). Although the hardness results of Lot W showed a variation between the bright and dark bands, they were less expressive when compared to the values obtained in Lot C.

The smaller difference in the hardness values for the Lot W could be due to the smaller quantity and extension of the banding present in the steel. Fig. 3b presents the microstructure of the quenched and tempered base metal, in which the presence of the bright bands was less significant, confirming a variation in the degree of banding between the two Lots evaluated in this work.

3.3. Microstructural evaluation in welding with two-layer deposition

The results of the semi-V joints welded with the two-layer temper bead welding technique in both base metals are presented below (cross section of the bevel faces). In both cases, the existence of the light colored bands was confirmed for the as-welded state. This shows that the multiple heat inputs were not sufficient to redistribute Cr within the material through diffusion (Fig. 4a and c). Fig. 4b shows the zones of the welded sample with the two-layer temper bead welding and submitted to PWHT. Notice that there is a reduction in the quantity of banding (bright bands) with PWHT, presenting a much more homogeneous microstructure than those seen in samples without PWHT.

Scanning electron microscope analysis was carried out on the points A, B, C and D highlighted in Fig. 4 to check for possible differences between the micro-constituents for the two conditions. In Fig. 5 details of the banding microstructure can be seen in a partially refined region, of the sample welded with the 15/5 kJ/cm heat input relation without PWHT (Lot C), still with coarse grains, forming a localized brittle zone (at point A). The bright band was made up of a large block of martensite associated with a fine structure and with needles in its interior. Using a higher amplification it can be seen that the structure in question is needles of lower bainite (Fig. 5b). It is probable that this region underwent a re-tempering due to the inadequate combination of the first and second layer conditions.

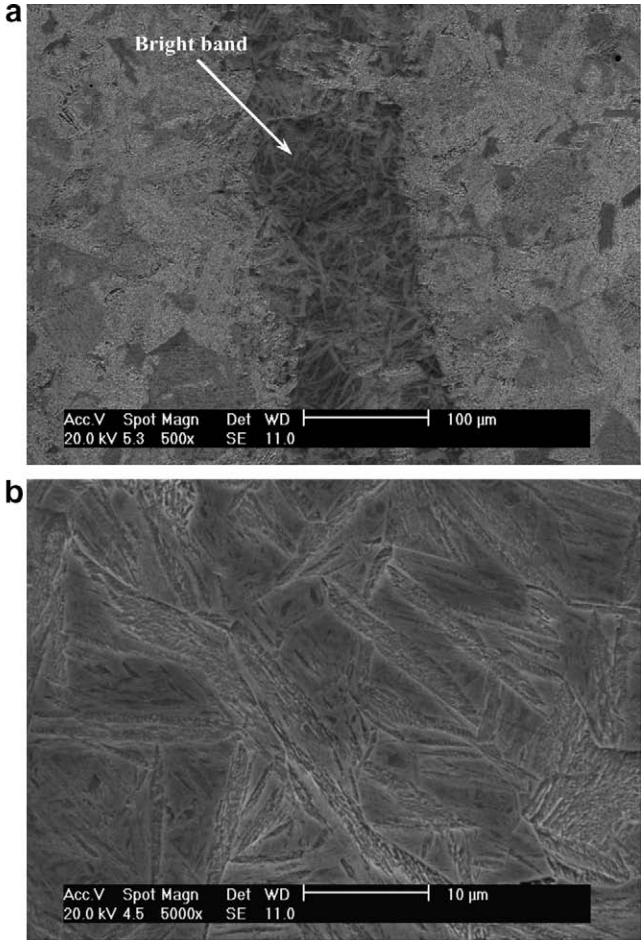

Fig. 5. (a) Banding microstructure in the partially refined zone (Lot C). (b) Enlarged detail of Fig. 5a showing the presence of needles of lower bainite inside the martensite. Sample welded with relationship 15/5 kJ/cm without PWHT.

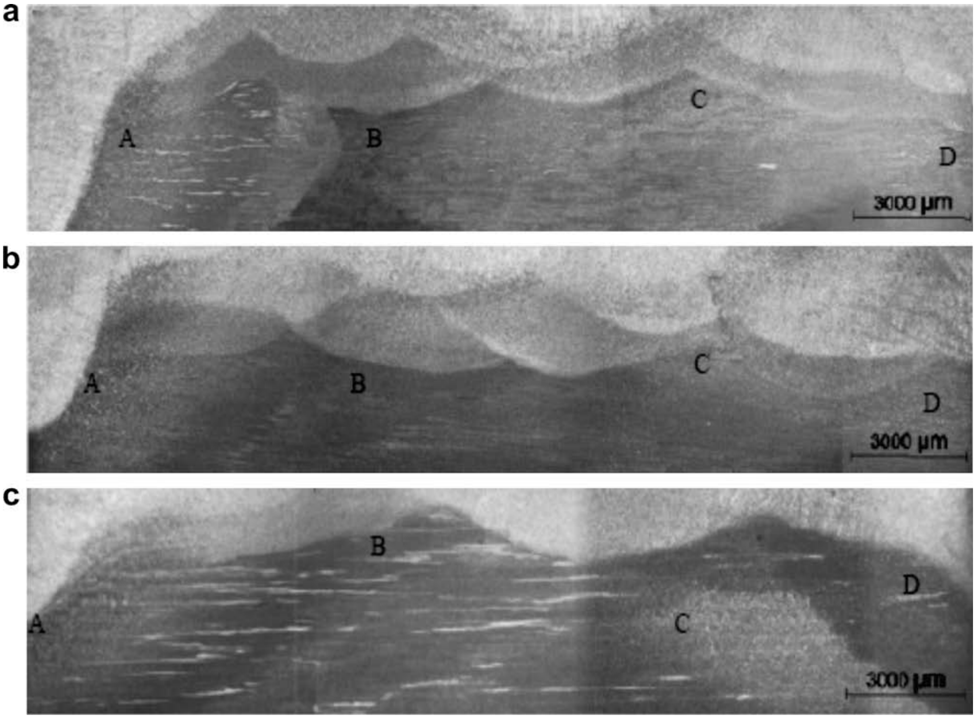

Fig. 4. Double layer welded joints of the Lot C. (a) Sample welded with relationship 5/5 without PWHT. (b) Sample welded with relationship 5/5 with PWHT. (c) Sample welded with relationship 15/5 without PWHT.

In a similar region for the sample submitted to PWHT (Lot C) the presence of martensite and upper bainite was observed (Fig. 6a and b). In this case some carbonate precipitates can be seen in the interior of the martensite, resulting from the tempering by PWHT.

3.4. Evaluation of the Charpy-V impact test

The results of the Charpy-V impact test for the sample from Lot C presented a significant variation in terms of energy absorbed between the test samples with and without PWHT (Fig. 7). The samples that underwent PWHT absorbed a greater level of energy when compared to the samples in the as-welded state (without PWHT).

The evaluation of the fracture surface of the Charpy test samples confirmed a very homogeneous behavior in the area of the brittle fracture (center of fracture) of the samples submitted to PWHT (Fig. 8a). The same behavior was not observed for the samples without treatment (Fig. 8b). The presence of bands along the fracture surface in the region of the brittle fracture was confirmed. Using SEM details of the fracture surface (Fig. 9) characterized for bands intercalated in the brittle fracture and ductile fracture can be seen. The enlarged detail of region A indicated in Fig. 9 is shown in Fig. 10a, where the presence of dimples characterizes a ductile fracture. The region of point B presents cleavage facets, indicating a process of brittle fracture (Fig. 10b).

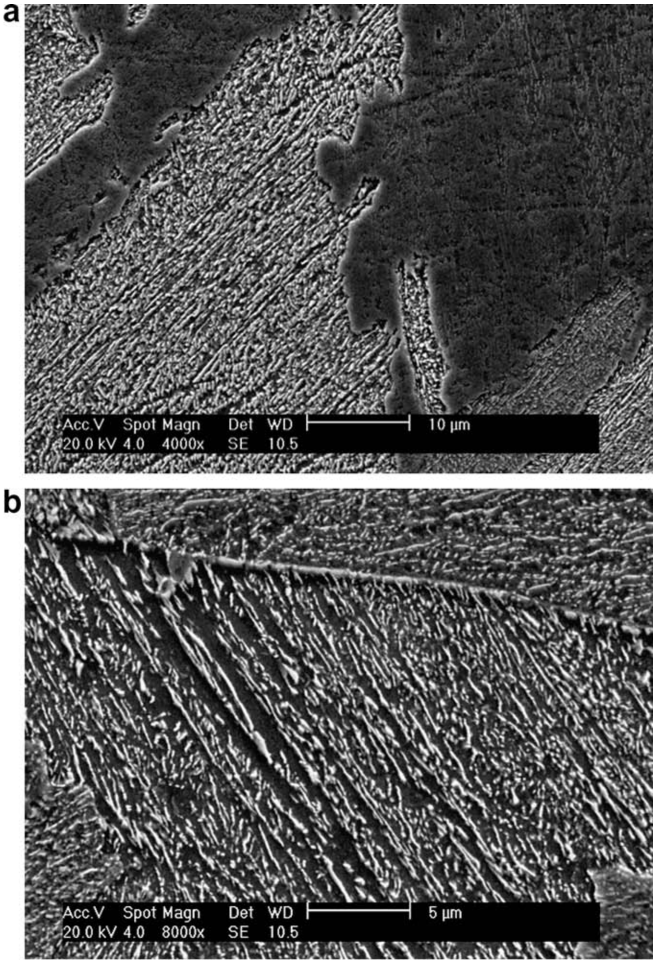

Fig. 6. (a) Microstructure of a dark band in the partially refined zone of the sample welded with relationship 15/5 kJ/cm with PWHT (Lot C). (b) Details of an upper bainite.

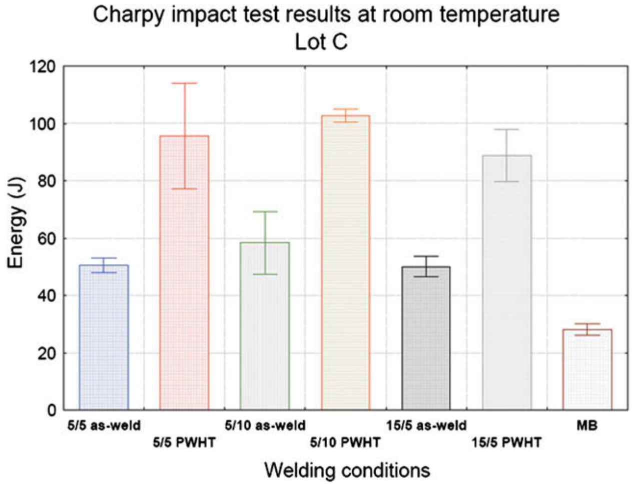

Fig. 7. Results of the Charpy-V impact test at room temperature – Lot C.

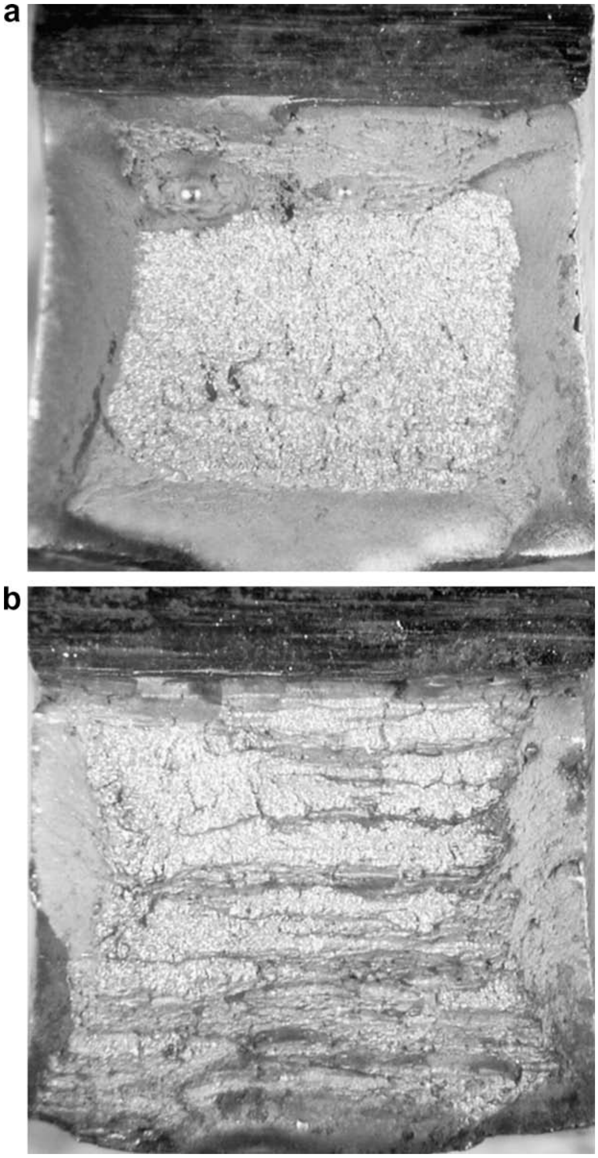

Fig. 8. Aspect of the fracture surface of the Charpy-V test specimen – Lot C welded with relationship 5/5 kJ/cm: (a) with PWHT and (b) without PWHT.

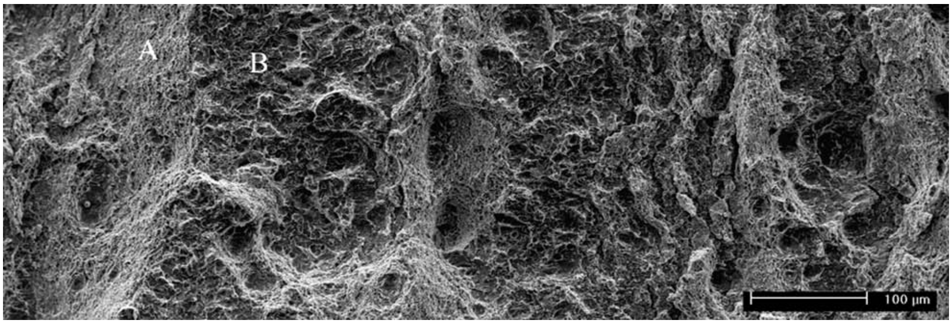

Fig. 9. SEM of the fracture surface of the Charpy-V test specimen of the sample welded 5/5 kJ/cm without PWHT (Lot C).

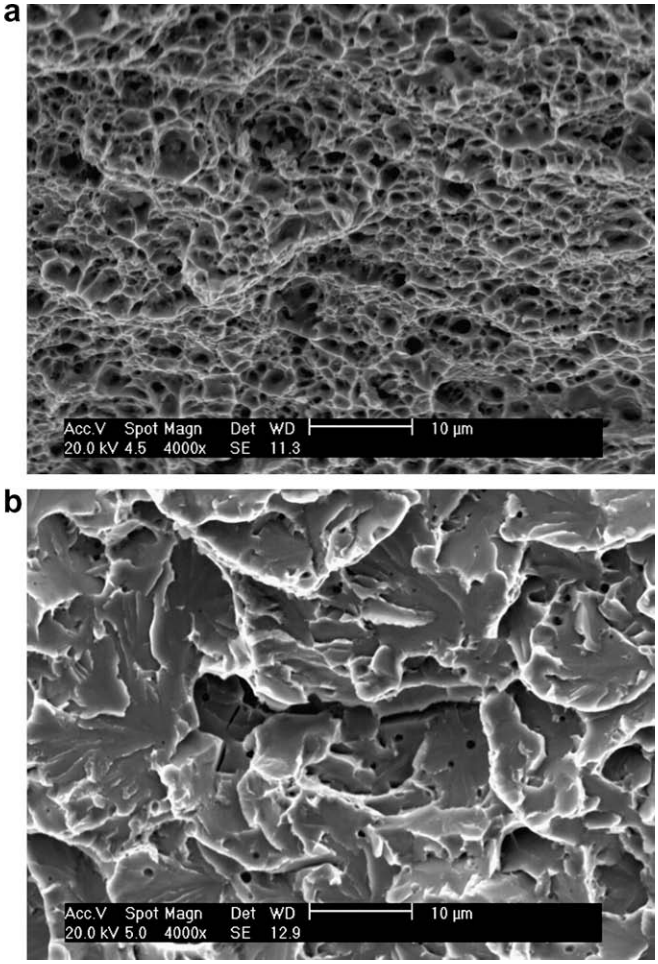

Fig. 10. (a) Fracture surface of A point indicated in the Fig 9 and (b) fracture surface of B point indicated in the Fig 9.

The presence of the ductile and brittle bands on the surface of the Charpy-V test specimen could indicate that banding has a role in the fracture process. It is probable that the ductile regions were made up of dark bands, with lower quantities of Cr and C and therefore were more ductile and tougher. However it is important to point out that the presence of banding does not mean a critical defect, since that even for the two-layer deposition welded samples without PWHT, the energy levels reached in the Charpy-V impact test were satisfactory, similar to the values reported in literature for 4140 steel in the quenched and tempered condition.

The samples of Lot W presented a very distinct behavior compared to Lot C in terms of energy absorption in the Charpy-V impact tests (Fig. 11). Independent of the heat input relation between the first and second layer, the results obtained for the condition as-welded were practically equal to the results of the material submitted to PWHT. This is considered positive, since it shows that the tempering provided by the two-layer temper bead welding technique was satisfactory. Besides this, the results show that the welded test samples presented greater energy levels absorbed than the quenched and tempered base metal under various conditions.

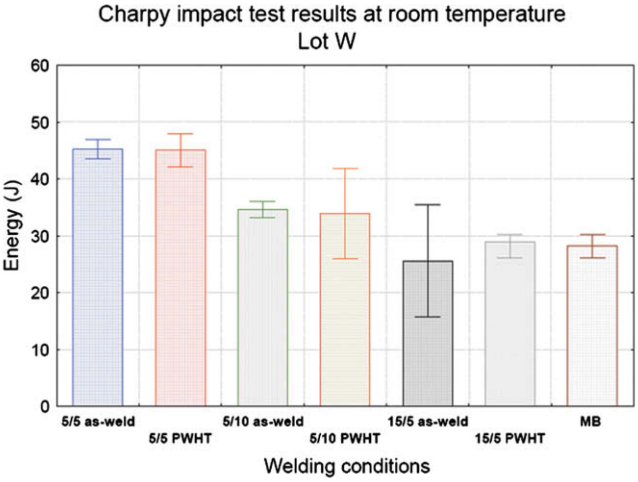

Fig. 11. Results of the Charpy-V impact test at room temperature – Lot W.

However, comparing the results of the test samples of both lots submitted to PWHT, there was a significant variation between the values of energy absorbed in the Charpy-V test. This significant variation could be due to the high quantity of nonmetallic inclusions in one of the base metals evaluated (Lot W). Independently of whether the tempering was produced by the two-layer temper bead welding technique or by PWHT, the presence of large quantities of inclusions extending along the lamination could concentrate stresses. These inclusions could act as a nucleation for cracks, or even, favor their propagation. Besides this, in all the cases, whether it is due to the superimposition of heat inputs or the association of heat inputs plus PWHT, the impact energy levels at the HAZs were better than the levels reached by the base metals quenched and tempered under various conditions. This observation indicates that in both welding procedures (with and without PWHT), the recuperation level of toughness of the material through tempering had reached a level limited by the effect of the intrusions.

The Fig. 12a and b show the presence of MnS inclusions in the fracture surface of Charpy-V test samples for Lot C and Lot W, respectively. Generally speaking the fracture surfaces of Lot C test samples presented an inexpressive quantity of inclusions, and

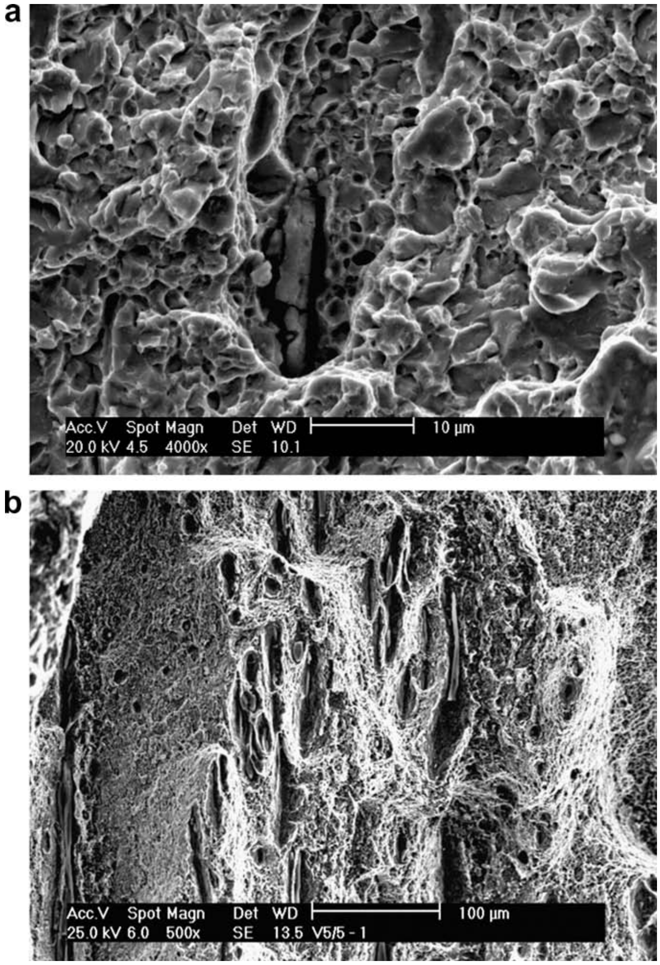

Fig. 12. Aspect of the fracture surface of the two Charpy-V test specimens welded with relationship 5/5 without PWHT. Presence of nonmetallic inclusions (MnS): (a) Lot C and (b) Lot W.

when found, were very short. On the other hand the Lot W analysis indicated once again a large quantity of elongated inclusions with considerable lengths along the fracture surface.

To round up, from a general point of view the main defect found in the Lot C base metal was banding, which causes a significant increase in hardness between the regions (bright bands and dark bands) and could have resulted in variations in the quantity of energy absorbed in the Charpy-V impact tests. This result shows also that even with banding, tempering plays an important role in increasing toughness. Therefore, the two-layer temper bead welding technique can be applied successfully with materials that present a high degree of banding since the energy values absorbed are compatible with those normally reported in the literature [15].

In the Lot W base metal there was an association of two effects, the banding and the presence of large quantities of nonmetallic inclusions of MnS. Although the presence of banding was not discarded, the presence of the inclusions was considered decisive for the lower toughness levels obtained in the Lot W evaluation. This result shows that the base metal characteristics can significantly affect the toughness of the welded joint so it is essential to make the correct choice of welding heat input for the layers and have a rigorous control of parameters during welding when using the two-layer temper bead welding technique.

4. Conclusions

Based on the results presented concerning the success of the two-layer temper bead welding technique with low alloy AISI 4140 steel base metals, with metallurgical defects such as banding and nonmetallic inclusions, it was possible to conclude that the banding, besides causing heterogeneousness in terms of hardness, causes a significant reduction in toughness, although the values obtained were still above those found in the quenched and tempered base metal. The two-layer temper bead welding technique was able to minimize the effect of banding, proportioning toughness levels above 40 J for the material in Lot C. The presence of a large quantity of nonmetallic elongated inclusions with expressive lengths presented a critical factor for the toughness of these steels. For materials with a high inclusion content, as seen in Lot W, the two-layer temper bead welding technique was efficient from the point of view of improving the welded joint properties, especially toughness, presenting results similar to those obtained with PWHT. Although the two-layer temper bead welding technique was successful in the two materials evaluated, it should be pointed out that the characteristics of the base metal to be recuperated could influence the final mechanical properties, making a prior evaluation of the base metal before applying the technique fundamental.

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