# REPAIR WELDING OF INJECTION MOLDS MANUFACTURED IN AISI P20 AND VP50IM STEELS

**Tafur P., Wilson**
UFSC
tafur@labsolda.ufsc.br

**Niño B., Carlos Enrique**
UFSC
cenino@emc.ufsc.br

***Abstract.*** *This work aims to study the adequate welding conditions to perform the repair of AISI P20 and VP50IM steels during the manufacturing of polymer injection molds, in order to obtain similar performance of the welding zones and base metal in polishing and texturizing treatments. Welding beads were done by TIG process, with dissimilar filler metal for P20 steel, AWS A5.28-96 ER 80S-B2, and two filler metals for VP50IM steel, similar and dissimilar, AWS A5.28-96 ER 80S-B6. Weld deposits were evaluated in relation to the quality of polished and texturized surfaces. Multipass welding techniques were optimized based on results generated by the bead implant test, analyzed using an analytical heat transfer solution and weld simulation with a CAD tool. Confirmation tests done with the producedures developed shown that for P20 steel it is necessary to apply the double layer technique. For VP50IM it is possible to obtain satisfactory results with a simple layer, particularly when using a similar filler metal.*

***Keywords:*** *Repair welding, polymer injection molds, mechanized TIG , polishing, texturizing*

## 1. Introduction

Polymer injection molds frequently require some form of repair by welding during the manufacture, due to the errors in machining or part design changes. High cost of materials and machining for the fabrication of molds with great geometric complexity, almost always justifies the repair of defects by welding, even though it is difficult to avoid negative effects of welding on the surface quality (after polishing or texturing treatments). In polymer injection molds it is necessary to confer to the repaired area similar characteristics from the base metal, since these defects would be reproduced in the injected part.

In conventional mold steels (quenched and tempered), one traditional way to minimize the embrittlement and to improve evenly texture and polished surface, is the use of preheating and/or postweld heat treatments. However, heat treatments are normally expensive and lengthy, not only by times necessary to relieve the stresses, but also by low heating and cooling rates necessary to avoid cracking by thermal stresses (Bueno, 1999).

Problems in the welding of molds are becoming minimized with the use of precipitation hardened steels, because the structure of the entire part - and not only the welded region - can again be restored through aging treatments, done at moderate temperatures, below the critical transformation temperature for austenite (Frederick, 2000). Weld HAZ on precipitation hardening steels is softer than QT steels HAZ, making easier to obtain an invisible weld after surface treatments (Cerwin, 2000).

The present work consists of a comparative study between AISI P20 steel (hardened by quenching) and VP50IM steel (precipitation hardened), employed in polymer injection molds fabrication. There were developed welding procedures through a new methodology, in order to improve weld surface quality. Weld quality was assessed in relation to the surface obtained through polishing and texturing treatments.

## 2. Some aspects of mold steels weldability

According to AWS D1.1-98 apendix B, weldability is: "the capacity of a material to be welded, under imposed conditions of manufacture, with a specific and appropriate projected structure in order to get a satisfactory performance in the service that it is intended". So, particular properties required for polishing and texturing treatments of molds constitute an additional factor to consider in steel weldability of molds, beyond the susceptibility to hydrogen cracking, thermal stresses and distortions produced by welding.

Due to the high hardenability of common mold steels (that enable air quenching), it is impossible to avoid totally the occurrence of martensite, prone to hydrogen cracks depending upon the carbon and alloy elements content. An increase of alloy content improves hardenability, wear resistance and dimensional stability. However, it impairs weldability. The main element that affects the weldability is carbon; when carbon content increases, martensite becomes harder and more fragile. The influence of carbon and alloy elements hardenability can be quantified through carbon equivalent, an expression of which frequently used for tool steels is that from the International Institute of Welding, IIW:

$$CE = \%C + \%Mn/6 + \%(Cr + Mo + V)/5 + \%(Ni + Cu)/15 \quad (1)$$

Tool steels weldability as a rule is low, because they have moderate carbon content (0,2% carbon) and carbon equivalent that exceeds 1%. This render those materials sensitive to hydrogen cracking.

With the increase in size of the component being welded, heat transfer increases in weld deposits and, therefore, the application of the preheating wins a bigger importance. To repair by welding molds of ferritic steels of high thicknesses it must be used preheating, to assure that the weld deposit cools at low enough rates to prevent cold cracks. When applying preheating, it is important not to exceed an interpass temperature of 300 $^{o}$C, in order to restrict grain growth on the HAZ, because it would reduce the resistance of the repaired region (Lant, 2001). To fulfill both of that requirements is suitable to use multipass welding techniques (Kou, 1997).

**2.1 Welding processes utilized on welding repair of molds**

Some processes are commonly used for repairing of molds: laser welding, resistance welding and TIG and plasma arc welding. Among them, in Brazil the TIG is mostly used, because of its relative low cost and greater availability of qualified workmanship for that application.

When welding by TIG using lower current levels, up to 100 or 150 A, as is the case of repairs on thicker parts, there is recirculation of liquid on the weld puddle, so the convective flow caused by Marangoni forces is preponderant, and surfactant elements such as sulphur govern the direction and intensity of these flows. The convective flow is produced passing from a region of low surface tension to a region of high surface tension. This type of mass and heat transference is the one that determines the mechanism of penetration of the weld bead (Mendez, 2003).

It has been verified that small changes of sulphur concentration on the fused metal promote significant variations in the surface tension. For the majority of pure metals, including iron and steels with low sulphur content, less than 70 ppm, surface tension decreases with the temperature. In this in case, surface tension is bigger in the cold regions (in the contour of the weld pool) inducing metal flow in the radial direction from the center for the outer region of the pool, which causes fused metal to act as an isolating layer hindering the transference of heat to the solid metal.This produces wider welds with low penetration, as indicated in Fig. 1 to the left. On the other hand, steel with more than 70 ppm sulphur shows a flow directed from the outer region to the center, which causes a deeper penetration and a narrower bead, as shown in Fig. 1 to the right (Mills, 1998).

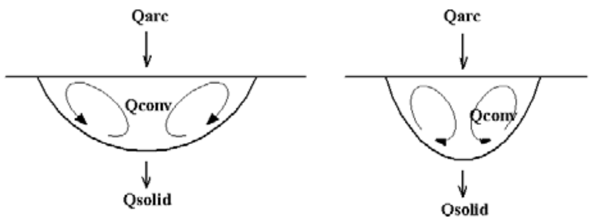


Figura 1 - Penetration mechanisms in TIG welding at low currents

**2.2 Welding of AISI P20 steel**

Steel AISI P20, of medium carbon content tipically around 0,35 %, is supplied in the quenched and tempered condition with a hardness of 30-32 HRC. It has a long history of success in the industry of molds of injection of plastics, however with serious problems when repaired by welding, when it is indispensable a post weld heat treatment for tempering and stress relieving, with negative effects on dimensional stability, necessity of machining rework and lower productivity.

By using multipass repair techniques without posterior heat treatment, as the double layer and temper bead techniques, heat from the arc can be used to thermally treat the HAZ and weld metal, in order to obtain appropriate microstructures to respond uniformily to posterior treatments and/or the service intended for the welded component (Niño, 2001). In the particular case of molds for polymer injection, it is important to get an uniform surface texture in all the regions of the welded component.

In double layer technique it is used a controlled method of deposition, in such a way that the second layer promotes the refining and reduction of hardness of the HAZ created by the first layer. Its effectiveness depends on the correct relation of energies between the welding passes and, furthermore, on the welding conditions selected for the particular base and filler metals and component geometry (Henke et al. 1998).

The effects produced in the HAZ of the first layer by the heat of the second layer are illustrated on Fig. 2a, that at the left shows the regions of the weld in a simple bead. As a rule, one can consider for ferritic steels that in a band below the Ac1 isotherm will occur tempering, between Ac1 and Ac3 isotherms partial refining and tempering, between Ac3 and approximately 1100 $^{o}$C refining and above 1100 $^{o}$C grain growth and quenching. The most important parameter to obtain refining and tempering of the coarse grain region of the first layer is the penetration of the Ac1 isotherm of the second layer. Relation of this parameter with the welding conditions can be evaluated on measures carried out in simple deposits representative of each layer (Niño, 2001).

The temper bead technique consists in getting the named "temper bead" adequately positioned in relation to the pass to be tempered, in such a way that Ac1 isotherm of first one coincides exactly with the fusion line of this last one (Fig. 2b). Thereby, the reaustenitized region of the pass to be tempered would be weld metal - which, in general, is not susceptible to develop high hardness-, while its HAZ would be reheated in temperatures below those of reaustenitization. This technique is used exclusively to temper the CG-HAZ produced in the base metal close to the part surface (Niño et al. 2001).

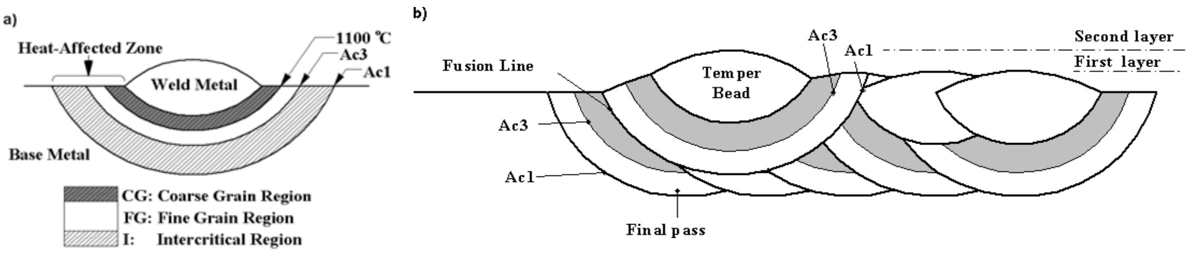


Figure 2 - a) single weld bead regions nomenclature; b) double layer and temper bead techniques.

### 2.3 Welding of VP50IM steel

VP50IM steel is supplied in the solubilized condition, with a low hardness (32 HRC approximately). After an aging treatment done at moderate temperatures (tipically 500 ºC) it reaches a 40 HRC hardness level, high enough to produce some stress relieving but not so high to cause significative distortions.

In VP50IM steel, sulphur content is higher than in conventional tool steels. VP50IM chemical composition is based on the Fe-C-Ni-Al-Cu-Mo system, developed to enable precipitation hardening by aging heat treatment, (Pinedo et al. 2005). In this steel, carbon makes possible to obtain a bainitic/martensitic microstructure after cooling from solution temperature. Nickel and aluminum are added to promote the hardening by aging, through the precipitation of intermetallic $Ni_3Al$. Moreover, the aluminum is essential to intensify the response to nitriding treatment. Copper improves machinability, promotes precipitation hardening and increases corrosion resistance. Molybdenum allows an additional hardening by carbide precipitation. As the weldability, structural integrity and HAZ properties can be improved with the reduction of carbon content, the design of new steels involves the use of lower carbon content (under 0.15%). Thus, cold cracking suceptibility is strongly reduced, making sometimes unnecessary the use of preheating (Frederick, 2000).

VP50IM steel was particularly developed in order to give an excellent weldability. After performing the weld, the mold must be aged. Making so, hardness differences between weld regions and base metal become smaller, resulting in a more uniform respond to polishing and texturizing surface treatments. Together with the VP50IM base metal a matching filler metal was developed, of similar composition, to be applied by TIG process.

### 2.4 Methodology

AISI P20 Steel was welded with a dissimilar filler metal, AWS A5.28-96 ER 80S-B2, which is a Cr-Mo suitable for welding components that operate at high temperatures, like boilers, pressure vessels and pipes. VP50IM steel was welded with two filler metals: a dissimilar one, AWS A5.28-96 ER 80S-B6, which is basically a 5Cr-0,5Mo steel, and a similar one. Chemical compositions of the base and filler materials are shown in Tab.1.

Table 2 shows the parameters adopted for welding by the mechanized TIG process. Process conditions were at first selected according to the experimental results obtained with AISI P20 steel, the most critical case. It was used direct current with constant amplitude, with a 225 ± 25 $^{o}$C preheating temperature (Tafur, 2005). After performing single weld beads on plates of 15 mm thickness (in the two materials), there were sectioned two specimens, one for microstructural analysis and hardness measurement and the other for grinding, polishing and texturing operations.

Macrographs of the transverse sections to weld beads were observed in a stereoscopic magnifier. The hardness indentations allowed an easier localization of the weld regions. Photographied images were inserted and drafted in a CAD software, to carry out the HAZ and weld bead dimensions measurement, specially penetration and width of the Ac1 isotherm. The bead implant method was used to study the effect of welding thermal cycles on resultant microstructures and to optimize multipass welding techniques. The “bead implant” method is explained in detail in (Niño, 2001).

Tabela 1 – Base and filler metals chemical composition (% weight)

| | Material | C | Si | Mn | Cr | Ni | Mo | P | S | Cu | Al | Nb | Co | Ti | V |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| BM(a) | AISI P20 | 0,39 | 0,37 | 1,4 | 1,89 | 0,77 | 0,18 | 0,03 | 0,055 | 0,12 | 0,002 | 0,005 | 0,025 | 0,002 | 0,012 |
| FM(b) | ER 80SB2 | 0,09 | 0,58 | 0,54 | 1,33 | 0,04 | 0,51 | 0,01 | 0,006 | 0,03 | - | - | - | - | - |
| BM(a) | VP50IM | 0,17 | 0,21 | 1,4 | 0,27 | 2,95 | 0,28 | 0,03 | 0,09 | 0,9 | 0,85 | 0,0048 | 0,05 | 0,005 | 0,09 |
| FM(b) | ER 80SB6 | 0,08 | 0,39 | 0,53 | 5,9 | 0,06 | 0,54 | 0,004 | 0,013 | 0,07 | - | - | - | - | - |
| FM(a) | Similar | 0,14 | 0,1 | 1 | 0,24 | 2,92 | 0,27 | - | 0,13 | 1 | 0,35 | 0,004 | 0,024 | 0,003 | 0,064 |

(a) Compositions measured through optical spectrometry.
(b) Compositions extracted from the manufacturer quality certificate.

Table 2 - TIG process welding conditions

| | |
|---|---|
| Current | 124 A |
| Voltage | 11 V |
| Welding speed | 10 cm/min |
| Heat input | 10 kJ/cm |
| Welding arc power | 1300 W |
| Shielding gas | Argon; 12 l/min |
| Nozzle diameter | 10 mm |
| Electrode: W+ 2%$ThO_2$ | diameter: 2.4 mm, tip angle 60° |
| Arc length | 4 mm |
| Wire diameter | 1.2 mm |
| Wire feed speed | 0.5 m/min |
| Wire incidence angle | 25° from plate surface |
| Torch incidence angle | 15° from perpendicular to surface |

In this study, a 150x150x25 mm plate of the base metal had a half-circular 2 mm depth groove made, where later it was deposited a welding bead. From that welded plate there were cut by wire electrodischarge cylinders 20 mm in diameter, having the weld bead at its surface (Fig. 3a).

Figure 3b shows the implant cylinders removal. These cylinders were cut in 20 mm length sections, then inserted in SAE1020 150x150x21 mm plates with interference fit. Later, autogenous TIG passes were done at the plate surface, using two heat inputs: 10 kJ/cm and 20 kJ/cm. The lower figure is equal to the one used for the first pass, the higher is the double of that. To obtain those heat inputs, were used 124 and 248 A, respectibly.

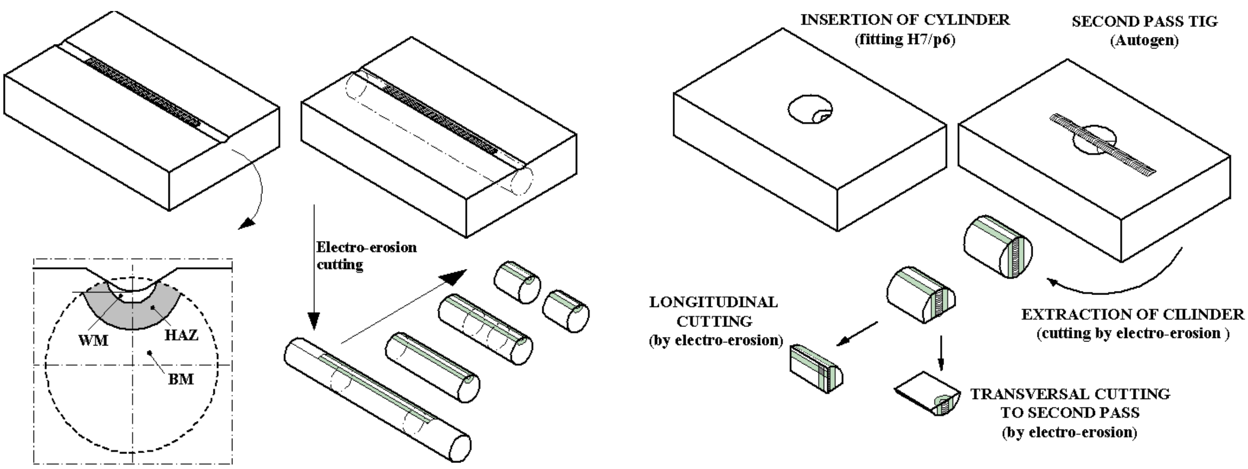


Figure 3 - Bead implant test procedure.

Implanted cylinders, that had been joined to the plate solely through the weld bead, were removed and sectioned by wire electrodischarge machining in the following way:

a) Transversally to weld bead, to prepare macrographs in which the bead and HAZ dimensions could be determined. That data was used as a input for an analytical solution of heat transference developed by (Santos, 2001), in order to obtain peak temperature distribution around the weld.
b) Longitudinally to both of weld beads, for hardness measurement.

The effects produced by the autogenous TIG pass on the previously deposited weld bead, were related with the peak temperatures and energy level, aiming to obtain the required data to optimize multipass welding techniques for the materials involved. For example, there were determined the positions of the second pass HAZ where microstructural and hardness variations would occur in WM and HAZ of the first pass.

To confirm the effectiveness of the welding procedures elaborated on the basis of the forementioned results, those procedures were applied in 150x150x25 mm plates of the base metals, having a 1 mm depth 25 mm width groove done previously by milling. The double-layer and temper bead techniques were applied as shown in Fig. 4 to the left, using the same heat input for all the passes.

All the passes were string bead, with a 50 % overlapping, maintaining preheating and interpass temperatures in the range 225 ± 25 $^{o}$C. After welding the part was covered with thermal isolating fiber to reduce the cooling rate. For P20 steel the overlapping between passes in the second layer was 66%. The position of the temper bed was defined as a distance between the weld toes of the first and last bead. The overlapping of passes and the position of the temper bead were determined through simulation of welds in CAD. The welded plates were cut, grounded, polished and texturized. The size of the specimens was 90 x 45 mm, as shown in figure 4. On the mirrored surfaces hardness was measured on the WM, HAZ and BM regions. The texture quality was assessed in macrographs observed at 10X, that allowed to relate the depth of attack with the region being observed.

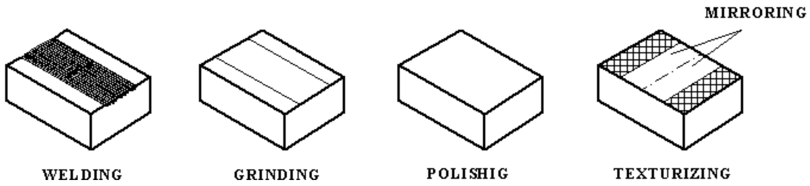


Figure 4 - Specimens for analysis of multipass welded metals properties and performance.

## 3. Results and analysis

In Figure 5, the characteristics of single pass welds are shown. At the top, the weld made on P20 steel with best results have no cracks in spite of the martensitic structure, and produced smaller relief differences between the weld and MB regions. This could be a consequence ot the higher dilution obtained with those conditions (Tafur, 2005), as this would result in a WM composition closer to that of BM.

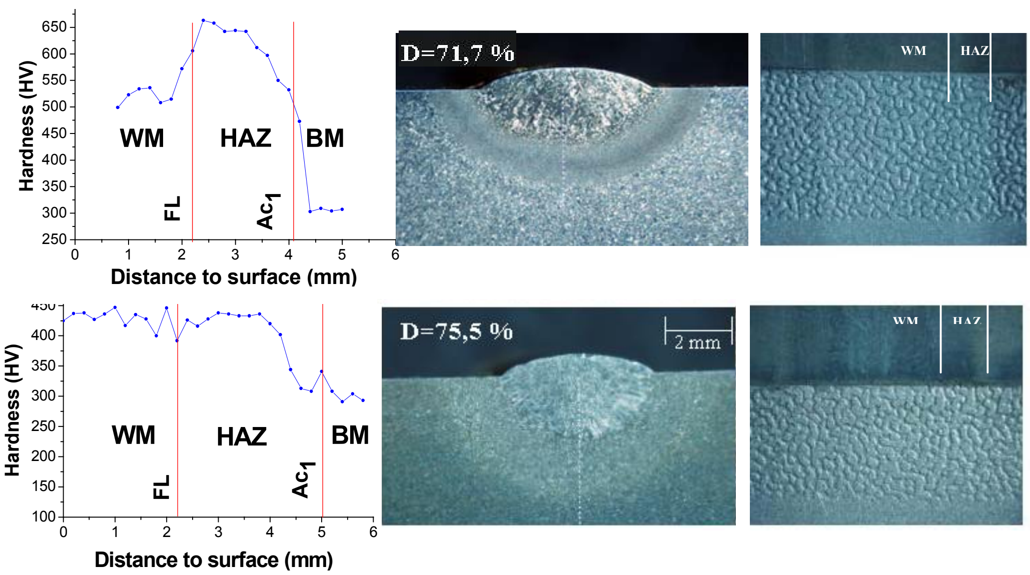


Figure 5 - Macrographs of the transverse sections of autogenous TIG weld beads made with low energy in: a) P20 steel; b) VP50IM steel.

At the bottom of Figure 5, the weld made on VP50IM steel using a dissimilar filler metal and then aged, shows a more uniform hardness profile and a regular depth of attack produced by texturizing treatment. In the WM and HAZ in both of the VP50IM specimens, welded with similar and dissimilar filler metals, the microstructure was martensite, and, as a result of the unusual high dilutions obtained for the TIG process (71 and 75% respectively), can be deduced that WM composition is similar to that of the BM. That would explain the uniformity in hardness throughout the weld. However, after the aging followed by mirroring the dissimilar weld showed relief differences. This difference can be due to the lesser amount of sulphur in the dissimilar filler metal, difficulted a WM removal by grinding (Tafur, 2005). So, this suggests that in order to get an excellent quality by mirroring, it is not enough to get a similar chemical composition through a high dilution, but also it is necessary to have similar sulphur content in the filler metal.

The sulphur content in the MB has a great influence in weld penetration. In both, welding with wire feeding (Fig.5) and autogenous welding (Fig. 6), can be observed the differences in the weld bead penetration and width when working with a lower sulphur content (55 ppm for P20 steel) and higher sulphur content (900 ppm for VP50IM steel). This confirms that besides arc characteristics the presence in the base metal of surfactant elements like sulphur have a strong influence on penetration, as mentioned in literature (Mills, 1998).

The penetration and width of the HAZ in welds made with low and high energy are shown in Tab. 3. In the columns at right side are shown the heat source parameters (the distribution parameter sigma and thermal efficiency), obtained through the thermal analysis solution. The transformation temperatures Ac1 determined by dilatometry were: 780 $^{o}$C for P20 steel and 765 $^{o}$C for VP50IM steel.

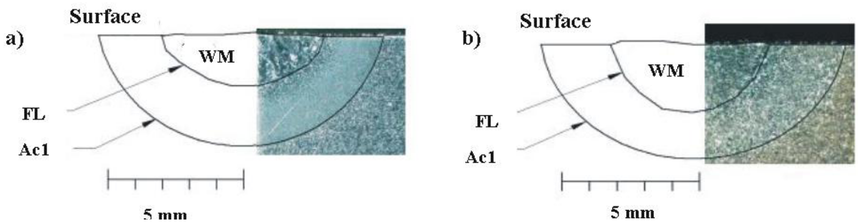


Figure 6 - Single bead characteristics: left, P20 steel; right, VP50IM steel welded with dissimilar filler metal.

In Figure 7 the profiles of hardness of WM, CG-HAZ and BM of the implant cylinder bead reheated by a second pass are shown. So, this profiles are in a longitudinal direction relative to the first pass. Also is shown the curve of peak temperatures produced by the second pass with low and high heat input.

Concerning the P20 steel (Fig. 7 top), it is observed that maximum tempering occurs at peak temperature Ac1. Defining as the tempering effect limit a final hardness of 450 HV (intermediate between the extreme values observed before and after tempering), there was determined the range of peak temperatures where that tempering effect ocurrs as a result of the second thermal cycle. This served as a base to define welding conditions for the application of double layer and temper bead techniques. For a TIG pass carried out with 7,81 kJ/cm, the region that experienced peak temperatures between 600 and 770 $^{o}$C was located at 4.1 and 5,6 mm from the surface, and the Ac1 was at 3,8 mm. The simulation in CAD for a multipass weld made with those heat input levels is shown in Fig. 8a.

It can be observed in the hardness profile of Fig. 8b that with double layer and temper bead techniques was possible to temper the CG-HAZ, which agrees with the foreseen. This allowed to obtain satisfactory polished, mirrored and texturized surfaces. To promote the hardness reduction by the temper bead, it was necessary to locate this with a tolerance of few tenth of mm, which was possible through the mechanized application of the TIG process.

Table 3 - Welding conditions and calculated heat source parameters.

| Base metal | Heat input | Current (A) | Voltage (v) | W. speed (cm/min) | HAZ penetration (mm) | HAZ width (mm) | Efficiency η | Dist.Par. σ (mm) |
|---|---|---|---|---|---|---|---|---|
| P20 | Low | 125 | 11,5 | 10 | 4 | 10 | 0,660 | 1,875 |
| | High | 248 | 13,6 | 10 | 6,8 | 17,8 | 0,620 | 3,679 |
| VP50IM | Low | 125 | 12,1 | 10 | 4,9 | 11,8 | 0,786 | 2,072 |
| | High | 248 | 15,3 | 10 | 7,9 | 20,6 | 0,650 | 4,314 |

In VP50IM steel welds subjected to aging treatment (Fig. 7 bottom) it was observed some overaging in reaustenitized regions by the second pass. This effect was more pronounced in high energy welds, were the hardness drop was around 300 HV. In face of this, a good option to repair VP50IM steel would be to apply a lower energy (8kJ/cm) for the deposition of the layer. After the aging heat treatmet, hardness variations are reduced so in the HAZ it ranges between 350 and 450 HV, similar enough to that of BM (450HV), then not being necessary the application of a second layer (Fig.7, center).

It can be observed in the hardness profiles (Fig. 8a and 8b), that with the deposition of a simple layer (overlapping 50%) it was obtained a more uniform hardness after the ageing treatment, compared with that of P20 steel. The differences of hardness in similar metal welds (400- 450 HV) were lower than that of dissimilar weld (350- 450 HV). However, in all the conditions, the surfaces produced by polishing, mirroring and texturing treatments had excellent quality.

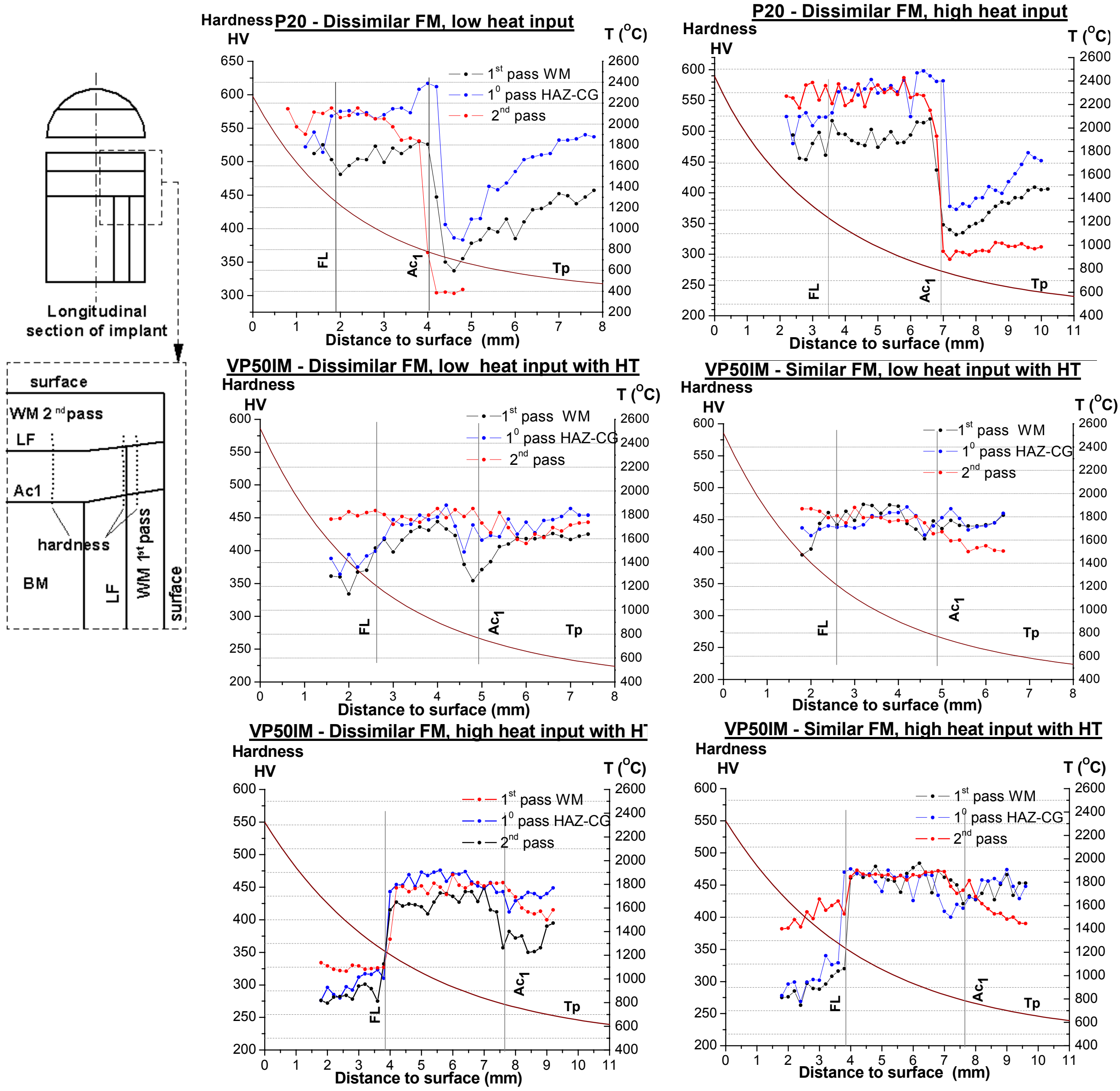


Figure 7 - Variation of hardness and peak temperatures on the weld regions of the first pass, produced by a second pass.

## 5. Conclusions

The repair welding using one single pass or one layer is not recommended for P20 steel, because the differences in hardness and microstructure between WM, HAZ and BM impairs the quality of the polished and texturized surfaces.

In order to obtain more uniform textures in repair welded AISI P20 steel, it is necessary to apply the double layer technique with a correct positioning of the temper bead, using a high overlapping of passes in the second layer and a similar energy to that of the first layer (in this study 8 kJ/cm).

In face of this, a good option to repair VP50IM steel would be to apply a lower energy (8kJ/cm) for the deposition of the layer. (Fig.7, center).

For VP50IM steel repair welding with a similar filler metal is not necessary the deposition of a second layer, because the aging heat treatment reduce hardness variations so in the HAZ it ranges between 350 and 450 HV, similar enough to that of BM (450HV), leading to satisfactory results in surface treatments. However, welding with a dissimilar filler metal (ER80S-B6) with only one pass can produce a relief difference in the polished surface, caused by the lower sulphur content of the WM. To avoid overaging on VP50IM steel it is recommended to apply a lower energy (8kJ/cm) for the deposition of passes.

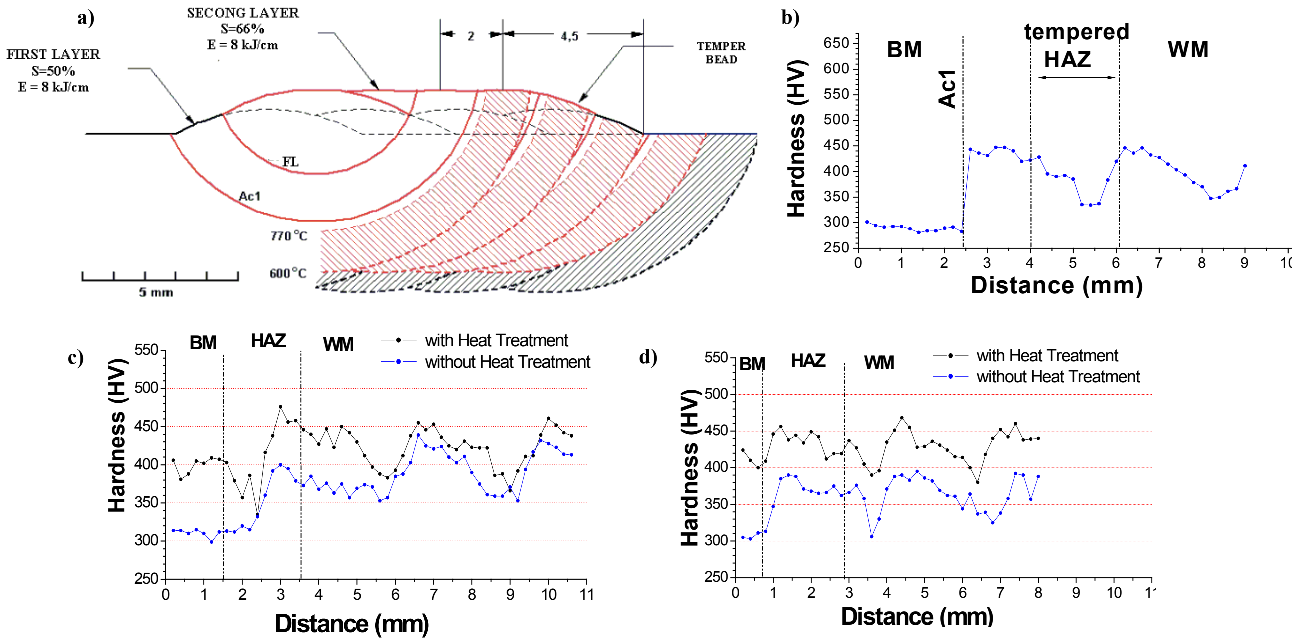


Figure 8 - Hardness variation on polished surface after multipass welding: a) Multipass welding procedure for P20; b) welding of P20; c) VP50IM dissimilar; d) VP50IM similar

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