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Peculiarities in Partial Melted Zone in Cast Alloys

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Abstract. The present work focuses the microstructural changes that occur in the partially melted zone of the welds made on some cast – designated alloys. The aim of this work is to improve the available data related to the PMZ morphology, properties and possible mechanism involved in the final metal response. It is demonstrated that for binary alloys little changes occur in the PMZ; in the case of a complex alloy the changes are more consistent and affects both primary and eutectic structure when interstitials are involved. It is also proven that the morphology of PMZ depends on the filler metal properties.

Introduction

Welding is a valuable method for automotive, aeronautic, ship building and many other industrial activities. The most common description of a welded joint implies three main zones: the base material(s), the melted zone and the so called heat affected zone (HAZ). The melted zone is the link between the parts; here the base metal and the filler metal undergo melting and overheating in liquid phase during the process. This implies an intense thermal shock for the surrounding material, so the solid state vicinities take the consequences: the heat affected zone develops under a steep thermal gradient. The overheated space between the melted metal and the solid metal is known as the partially melted zone (PMZ). Little attention has been paid to this tiny layer most of the concern has been oriented towards the first heat affected subzone.

Generally, before welding, the parts to be joined do support one or more technological processes (heat treatments, forming) in order to improve the metal structure. In "as cast" conditions parts are not commonly welded, the process being usually accepted for the repairing of the broken parts. Cast alloys have heterogeneous structure and properties, so the welding of the cast designated alloys is still a challenge. Therefore, periodically there is a special interest for some cast alloys and, during a short time, an intense activity is related to this. It is the case of cast irons in the 1970…1980 decade.

One can assume that among the first investigations related to PMZ were those which were done on the cast irons welds [1, 2]. Ishida (1985) describes the solidified PMZ for a grey cast iron as a "jumble" one; short after this for the same region the "graphite barrier" theory for the graphite cast irons being accepted.

In case of the welded steels the main concern related to the PMZ is the hot cracking sensitivity. Considered at the beginning as a consequence of the impurities content - that is mainly sulfur and phosphorus, the intergranular liquid film presence was a constant, even in the case of a low content of impurities. So, the hot crack sensitivity is still present in a heat treated metal if the alloy develops an eutectic reaction [3]. Many studies were conducted regarding the first subzone of the HAZ, the zone that has PMZ into its structure. This first subzone, also called the coarse grained HAZ is responsible for the hot crack sensitivity but also for the ductility and the impact strength loss subsequent to a welding cycle in most of the welded structures. For the processed alloys, heat treated or deformed, it is obvious that the PMZ consists often of a thin liquid film, so it can be frequently neglected as a distinct area. It is the case of the complex aluminum alloy studied in [4]. The PMZ is not mentioned in the article, but there it is summarized efficiently the possible mechanisms that can be involved in the microstructural changes in HAZ and in the fusion line.

For welding of the cast alloys an increased interest appears for the magnesium [5, 6] and nickel alloys [7]. The structural changes for the magnesium alloys are studied in the as cast conditions. It is concluded that melting and re-solidification of the metal into the PMZ have a major influence on the eutectic structure, changing the interface morphology of the phases in contact. The changes are, as it was expected, more intense into the close vicinity of the melted pool. Another important conclusion is that the welding process has an important effect not only on the PMZ extent (PMZ for an electron – beam weld being narrower than the TIG weld), but also on the segregation effect [7].

The nickel alloy is welded in overaged condition in order to avoid microcracking occurrence. The overall effect is similar to that registered in the case of the aluminum heat treated alloy, and crack occurrence is connected with the resolidified products: liquation products, precipitated metallic compounds and coarsened constituents.

In the present work it was performed a microstructure study on two different cast alloys, an aluminum silicon alloy and a white cast iron. The aim of it is to complete the information about welding the cast alloys, the best way to understand the peculiarities of the cast alloys behavior and of the main influences that affect the microstructure and, as consequence, the alloy properties into the PMZ.

Experimental procedure

Materials and welding details. For the proposed purpose an aluminum-silicon alloy EN AC AlSi12 according to EN AC 44300 (chemical composition of the samples: 11,7%Si, 0,478%Fe, 0,507%Cu, 0,186% Mn, 0,829 % other elements and balance Al) was poured into a mould. The plates of 100x25x5mm were obtained. The specimens were bead-on-plate TIG manually welded in two variants: the first one, no filler metal and the second one a bead on plate weld with AlSi5 filler wire. The welding regime was: 70A d.c. at 14V using a tungsten electrode with 1,6 mm diameter. The average welding torch speed was 120mm/min and 100mm/min respectively.

The chemical composition, spectrometrically determined, of the white cast iron (grade G-X300 CrMoNi 1521 according to DIN 1695) was: 2,5%C, 0,6%Si, 0,8%Mn, 17,5%Cr, 0,9%Ni, and 1%Mo. The prepared samples have had the dimensions 100x25x15mm.

The manual metal arc bead on plate welds were accomplished with two coated electrode grades: E 6013, a common steel electrode and a NiFe electrode. The diameter of the electrodes was 3,25mm and the welds were done with a 100A current.

The microstructure of the aluminum alloy in the cast state consists of dendrites of primary Al solid solution surrounded by a fine eutectic layer. According to the Al-Si equilibrium diagram the eutectic temperature is 577^0C. Silicon solubility into the aluminum matrix reaches at the eutectic temperature the maximum value, that is 11,7%Si and the eutectic forms just above 1%Si content. The microstructure of the cast AlSi12 alloy is presented in figure 1a.

The white cast iron microstructure in the cast conditions, according to equilibrium diagram of the Fe-Cr-C consists of a primary austenite and ($\gamma + M_7C_3$) eutectic, figure 1b.

Microstructure investigation. Each welded specimen was cut transversely to the weld axis and the metallographic specimens were prepared following the procedure to final polishing with 0,3mm alumina paste. The fresh polished surfaces were etched as follows: aluminum alloy with NaOH 10% solution in distilled water; white cast iron with nital solution (4ml HNO_3 in 100ml ethyl alcohol). Base metal specimens from both alloys were also prepared. The so prepared samples were examined by both optical microscopy (OPTIKA XDS-3 MET equipped with Optikam 4083.B5) and electronic microscopy (SEM) QUANTA 200 3D type, equipped with energy dispersive spectrometer (EDS) analytical system. Microhardness tests were conducted on both cases, HV 0,1.

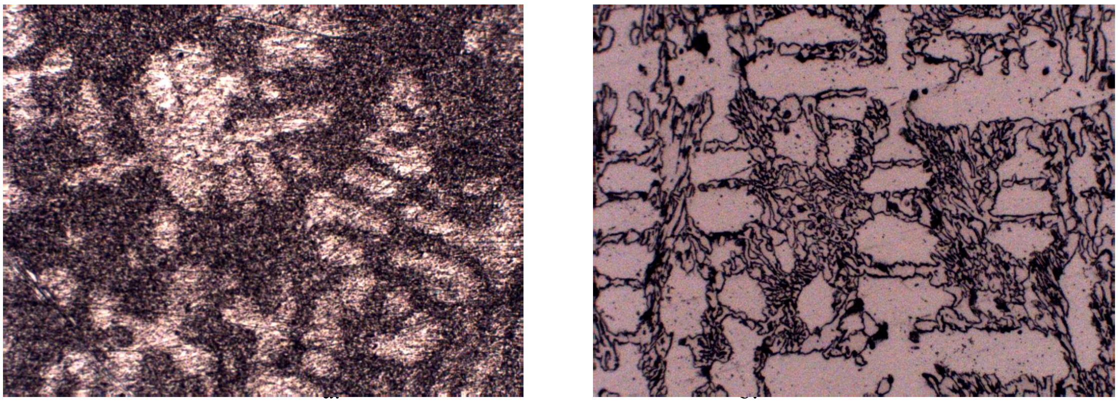

Fig. 1. Optical microscopy for the base materials: a. AlSi12; b. G-X 300. (x20)

Results

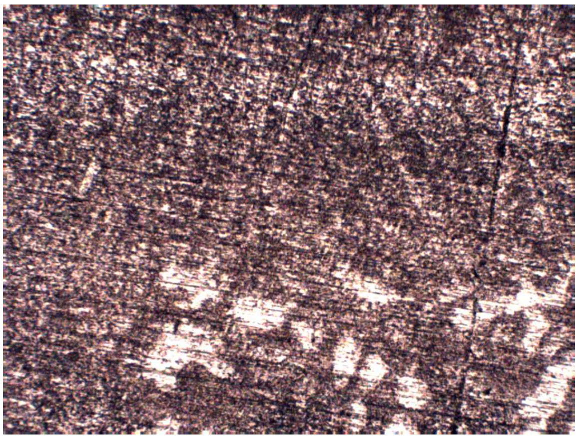

Fig. 2. PMZ in superficial melted AlSi12 (x20)

Aluminum alloy. The bead-on-plate melted sample exhibits an eutectic structure with small dendrites into the melted zone. Due to the rapid cooling of the liquid pool no primary Al dendrite could form. Also the PMZ is narrow because of the high conductivity of the alloy and the relatively small heat input. In PMZ the dendrites' interface is serrated and the distances between α solid solution islands are bigger.

In the case of the weld with added material, the PMZ has some interesting aspects, figure 3. From the base metal some dendrites emerge through the PMZ and reach to the deposited material.

The base metal dendrites coexist with fine, probably new dendrites formed into the melted metal, figure 3b.

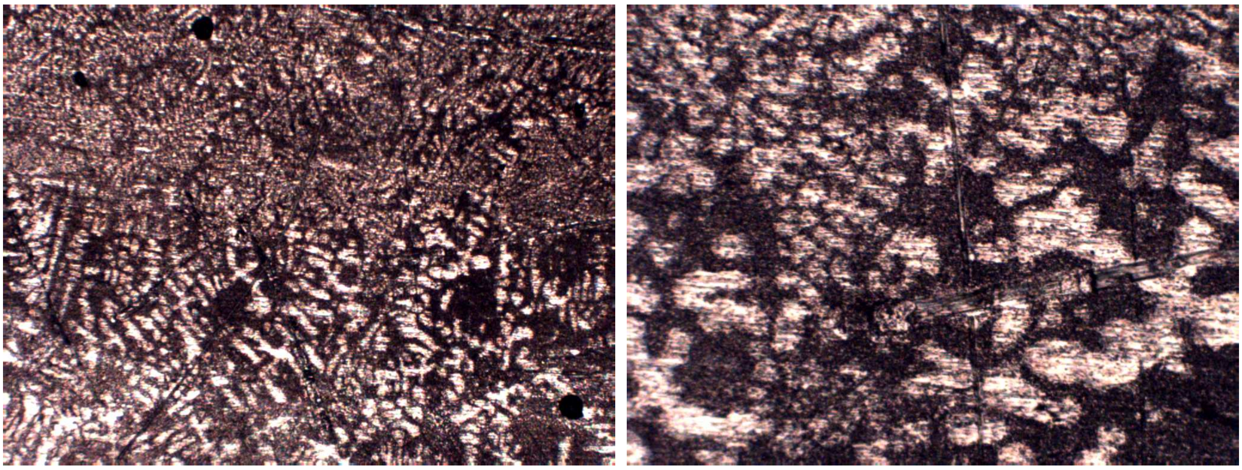

Fig. 3 Aluminum alloy AlSi12 welded with AlSi5: a. PMZ x5; b. PMZ – base metal, x20.

Chemical composition on the thermal gradient direction, obtained by EDS analyzer, denotes that no or too little diffusion occurs in the PMZ. The silicon content registers a steep difference between the two morphological different zones along the interface.

White cast iron base metal. The optical microscopy for both cases reveals that PMZ is large, with important changes in the structure, figures 4 a and 4 b. The PMZ width and morphology seem to depend on the filler metal composition.

In the case of the welds made with steel wire both interfaces between HAZ and PMZ and the ones between PMZ and the liquid pool are visible on optical microscopy.

The NiFe added metal weld produces a narrower PMZ, with reduced effect on dendrite's morphology. As the heat input was the same there are two aspects that must be considered.

In the first place, the effect of the difusion of all elements made out of cast iron toward the filler material , as consequence of the concentration gradient and secondly, the difference of solubility of the filler material for the carbon resulted from the disolved eutectic carbides.

Figure 4a shows that it appears a light layer, a martensite one, in the PMZ – filler metal interface in the case of steel added metal. In the NiFe filler metal case the interface aspect is almost that of a gray cast iron weld, with a dark, continuous layer surrounding the deposited metal. SEM microscopy confirms the above described features, figures 4.c and 4.d.

The fusion line in the case of the steel electrode is well delineated on both sides on SEM microstructure. In spite of this, the transition from the base metal to the weld is smooth, dendrites are embedded into a compact eutectic matrix, more compact than that of the base metal. The base metal dendrites, mostly oriented on the thermal gradient direction, are reaching the columnar growth region of the solidified metal, figures 4.a and 4.c. The homogeneity of the weld accomplished with steel electrode is confirmed by means of EDS analysis.

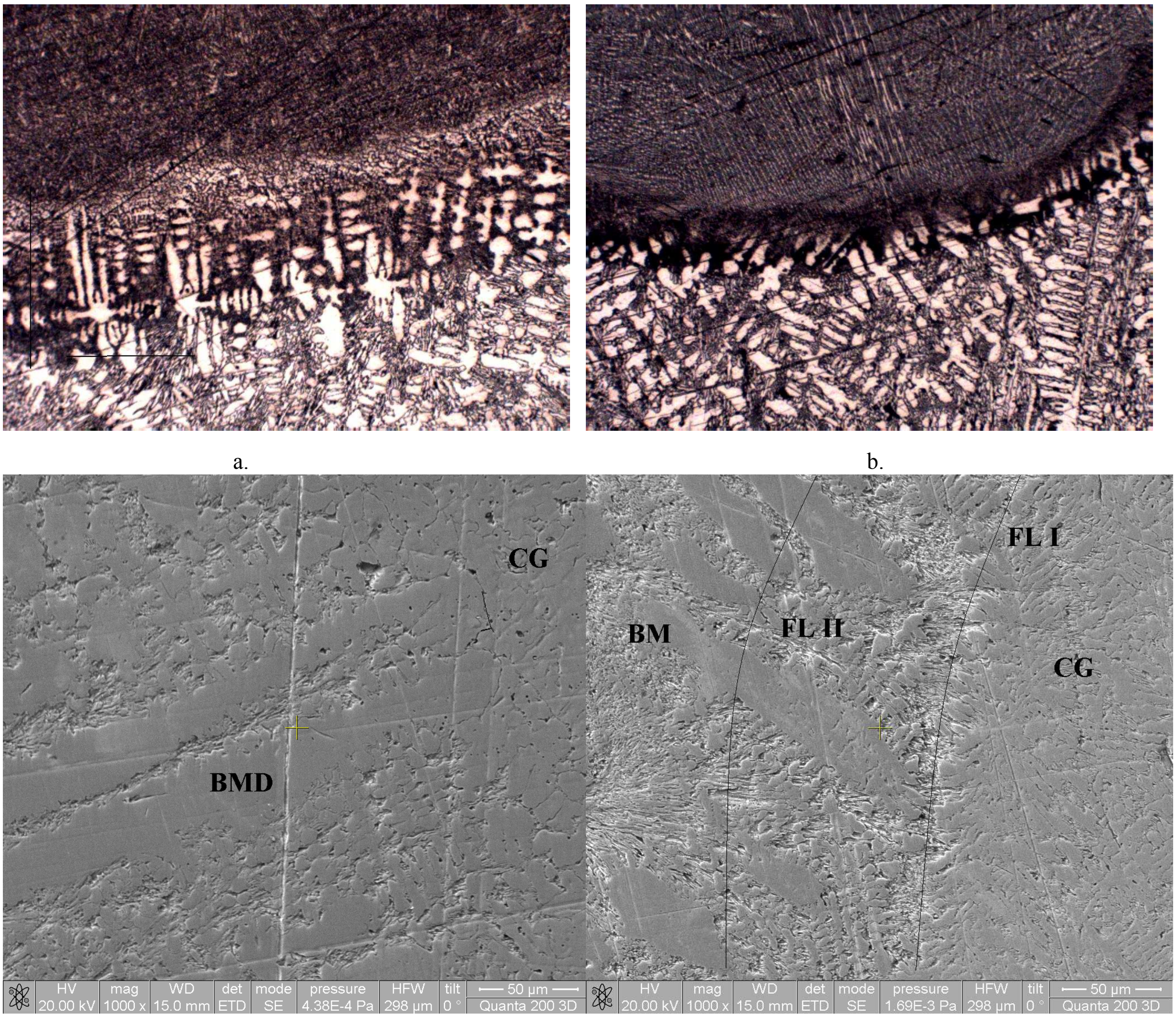

Fig. 4. Microstructure of the partially melted zone for the cast iron samples: a. optical microscopy image for steel electrode; b. optical microscopy for NiFe electrode (x100); c. SEM image of PMZ for steel electrode: d. SEM image for PMZ in NiFe electrode weld. BMD – base metal dendrite; CG – columnar growth in weld; FL I – fusion line: FL II - PMZ base metal interface.

In case of NiFe electrodes the contour of the weld pool is decorated with a porous structure that penetrates between the dendrites. Also, the extremities of the dendrites have a porous appearance, as it can be seen in figure 4.d on the marked dendrite, and in figure 5, point 1.

The compositional analysis of some special points in the PMZ, highlighted in figure 5, compared with the overall composition is presented in Table 1. According to the Table 1 the selected points are rich in chromium. The high chromium and carbon content into the interdendritic space, on the fibrous structure confirms the presence of the specific carbides.

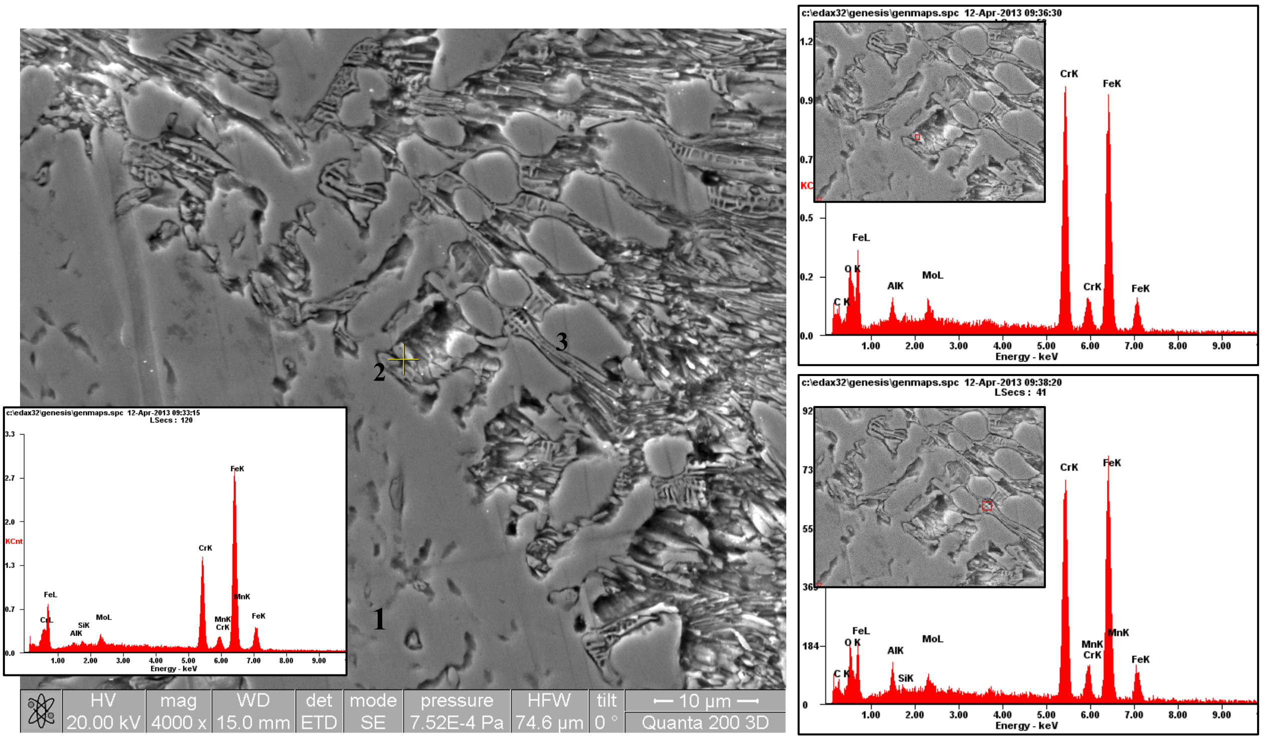

Fig. 5 Selected points for compositional EDS analysis and spectrum for the selected points.

Table 1 Chemical composition in some points in the PMZ, compared with HAZ and overall content

Element	Chemical composition, [wt%]				
	Nominal	EDS analysis, selected area			
		HAZ	1	2	3
Cr	17.5	17.25	21.58	32.73	31.58
Mo	1	1.98	2.92	3.11	2.84
C	2.5			3.96	3.38

Microhardness tests on the main phases were accomplished, see figure 6, revealing that both phases increase the hardness values after welding. On the same dendrite hardness was measured into the PMZ and outside of it, into the complete solid state material. The intimate changes into the solid solution did not influence consistently the hardness values.

Discussions

The solidification theory and all the equilibrium diagrams are based on the assumption of the existence of at least a local equilibrium. More precisely, is needed a very slow heating/cooling rate, so diffusion can control the process. But this is not a valid hypothesis in the welding case. The majority of cast designated alloys are containing an eutectic constituent.

In this particular case rapid heating involves melting first the eutectic structure. In PMZ theoretically only the eutectic structure experiences melting. Under the thermal gradient effect in PMZ the quantity of melted eutectic as well as the influence that this exerts on the dendrites morphology depends upon the relative position of the considered point from the fusion line.

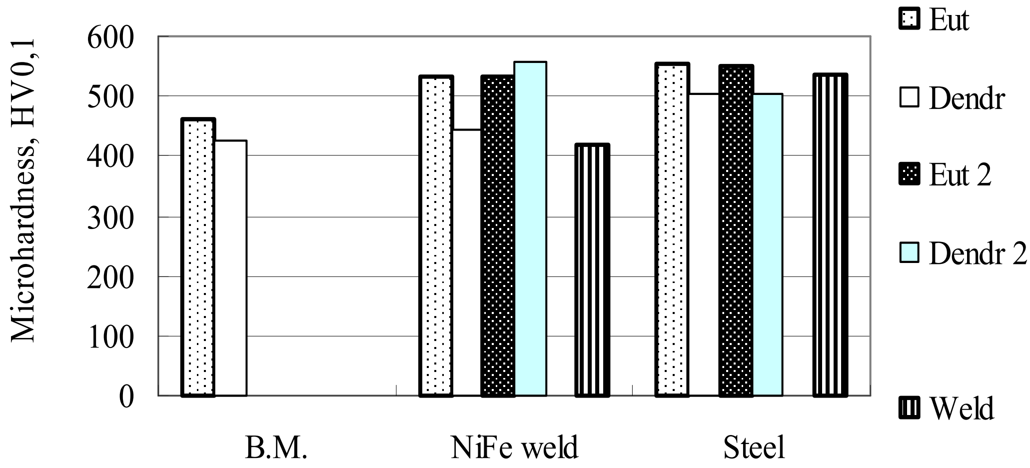

Fig. 6. Average microhardness HV 0,1 on the main phases. Eut – eutectic; Dendr – solid solution from the base metal and the PMZ; Eut 2 and Dendr 2 – same as before, into the unmelted base metal.

The experiment complies with this general theory. In all cases, the interdendritic space is larger near the fusion line, and the arms of the dendrites which penetrate the PMZ are serrated in almost the same distance with respect to the fusion line.

For the white cast iron, a multicomponent alloy, the most interesting aspect is related to the filler metal effect on the PMZ structure.

The chromium white cast iron solidifies at equilibrium begining with austenite. The solidified austenite is Cr rich, but an important amount of Cr is also into the remining liquid, Cr being also a strong carbide former. At the eutectic temperature it begins the eutectic – $\gamma + M_7C_3$ solidification, where the M_7C_3 is a rich chromium compund. Welding involves the melting of the former mentioned phases. In this experiment the eutectic composition ensures the the formation of a liquid in PMZ with a high content of Cr and C. this liquid founds itself in equilibrium with the solid solution, the dendrites, which have a different concentration of Cr and C.

In this quasiequilibrium state dendrites participate to the final liquid composition (the serrated interface), so when resolidification begins, the liquid composition is somewhat different. The interface instability could be due to the minor segregation effect at solidification. Resolidification dynamics depends on how components can redistribute along the PMZ, possibly into the filler metal.

At near solidus temperatures, carbon has a good diffusibility. In both situations from the experiment, the concentration gradient as well as the thermal gradient favour the carbon diffusion toward the fusion line. When the filler material is steel wire, the reduced carbon percentage from the liquid pool as well as the capacity of this pool to dissolve the carbon excess, permit the chemical homogenization and this way, ensures a structural continuity.

The nonferrous NiFe electrode liquid pool cannot solve the carbon amount, because Ni is a graphite forming element and do not form carbides. The excessive amount of carbon precipitates in graphite form. The local chemical composition allows it [8]. As a consequence, solidification of the PMZ is different and it can be observed even by optical microscopy, figure 4. a.

The changes into the dendrite's volume in NiFe weld could be related somewhat with the minor segregation at solidification, which affects dendrite's homogeneity. As it can be seen in table 1, those points are chromium rich. Under the thermal cycle small rearrangements can occur in the solid solution. In the steel case, this feature is not evident but it does exist.

Conclusions

The work in this paper focuses on the microstructure changes that occur on some cast alloys in the partially melted zone and the possible parameters that can determine those changes.

As a common observation, for the studied cases, is the participation of the primary dendrites to the material in the PMZ. This confirms previous observations [5, 6] for other cast alloys. The serrated interface accommodates eutectic colonies.

Homogeneity of the primary dendrites is also affected, but with little influence on hardness values.

For a weld pool that is capable to solve interstitials, in this particular case carbon, the PMZ appears as a homogenous zone. Otherwise, the liquid into the PMZ accumulates the migrating elements and this could influence this particular layer.

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