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# Influence of weld overlaying methods on microstructure and chemical composition of Inconel 625 boiler pipe coatings

M. Rozmus-Górnikowska*, M. Blicharski, J. Kusiński

*AGH University of Science and Technology, Faculty of Metals Engineering and Industrial Computer Science, al. Mickiewicza 30, 30-059 Krakow, Poland*

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**Abstract**

The aim of this work was to identify the impact of the welding method of boiler pipes made from P235GH and 16Mo3 steels on the microstructure and chemical composition of coatings. The investigations were carried out on a boiler pipes weld overlaid by Inconel 625 welded under various conditions (cold metal transfer (CMT), gas metal arc welding (GMAW) and gas tungsten arc welding (GTAW)). The microstructural examinations were performed on longitudinal cross-sectioned samples. The qualitative and quantitative chemical composition analyses on metallograpic samples were determined on SEM by means of energy dispersive spectrometry (EDS). The investigations showed that regardless of welding method the overlays consisted of the following microstructural zones: fusion zone, partially mixed zone, partially melted zone and heat-affected zone. The content of Fe, observed in all deposited coatings, was higher than the concentration of Fe in the Inconel 625 wire, however, it was within the basic technological requirement for the Fe content (< 5 wt.%). The Fe content was clearly higher in the partially mixed zone than in the fusion zone and decreased with the distance from the interface towards the coating surface. Close to the coating surface the highest Fe content was identified in the weld overlays that exhibited the least uniform fusion boundary and the least smooth outer surface. The most uniform external surface was identified in the coating deposited by the GMAW and subsequently fused by the GTAW method.

Key words: weld overlay, cold metal transfer (CMT), gas metal arc welding (GMAW), gas tungsten arc welding (GTAW), microstructure, chemical composition

## 1. Introduction

The boiler elements, most exposed to corrosion environments, are currently weld overlaid by a nickel alloy [1, 2]. The basic technological criteria to be met by nickel-based overlays are: the amount of iron entering from the base material (steel) into the coating should be as low as possible and the thickness of the weld overlay should not exceed 2.5 mm. An increased Fe content, resulting from the interdiffusion of the base material in the overlay, has a negative impact on corrosion-resistance [3, 4]. Inconel 625 alloy containing up to 0.5 % Fe is often used for cladding.

Weld overlaying is a process by which a layer of material is deposited on the surface of the base metal by welding methods. Comparing to coatings produced by other methods, weld overlays are characterized by strong metallurgical bonding with the base material, due to the interpenetration of the deposited and supporting materials, i.e., mixing of plating material with the substrate layer. Moreover, it is relatively easy to produce an overlay free from pores or other defects. The following methods are used for weld overlaying: gas welding (flame welding), arc welding, laser or electron beam welding. In the case of boiler elements large areas are welded. Therefore, the welding methods applied to this purpose should be fast, relatively cheap, but simultaneously, the coatings produced by this method should be of high quality. That is why gas tungsten arc welding (GTAW) as well as gas metal arc welding (GMAW) are most commonly used for this purpose [5, 6]. Recently, a new type of arc welding, referred to as cold metal transfer (CMT), with pulse wire feeding, has gained popularity in the industry.

*Corresponding author: tel.: 12 617 33 38; fax: 12 617 33 44; e-mail address: rozmus@agh.edu.pl

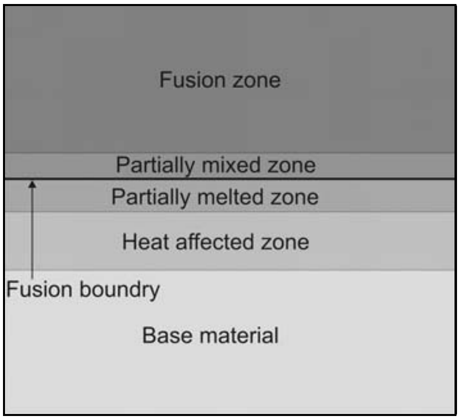


Fig. 1. Characteristic microstructural zones in dissimilar welds.

Table 1. Chemical composition of P235GH and 16Mo3 steels (wt.%)

| Steel | Fe | C | Si | Mn | Cr | Mo | Ni |
|---|---|---|---|---|---|---|---|
| P235GH | bal. | 0.16 | 0.34 | 1.20 | 0.30 | 0.08 | 0.30 |
| 16Mo3 | bal. | 0.16 | 0.34 | 0.65 | 0.30 | 0.30 | 0.30 |

Table 2. Chemical composition of Inconel 625 wire (wt.%)

| Alloy | Ni | Cr | Mo | Fe | Nb | Mn | Si | Al | C |
|---|---|---|---|---|---|---|---|---|---|
| Inconel 625 | bal. | 22.24 | 9.14 | 0.31 | 3.46 | 0.01 | 0.07 | 0.07 | 0.02 |

CMT is more energy efficient compared to traditional processes of welding and makes it possible to limit the coating thickness and reduce the dissolution of the base metal in the overlay [7–9].

The weld overlays, like dissimilar welds, consist of the four distinct microstructural zones: fusion zone, partially mixed zone, partially melted zone and heat-affected zone (Fig. 1). The fusion zone is a region where complete mixing occurs between the base material and the filler metal, therefore, the chemical composition of this zone is generally macroscopically uniform. In the partially mixed zone, the mixing between the base and filler metal is incomplete. Thus the chemical composition changes gradually across the weld interface. The zone adjacent to the partially mixed zone is referred to as the partially melted zone since the temperature in this zone lies between the liquidus and solidus for the base material. The chemical composition of this zone is identical to the composition of the base metal. The heat-affected zone comprises the region within the base metal, where the temperature during welding approaches the solidus of the base. Also, the fusion boundary is often distinguished as a characteristic feature of an overlay. The fusion boundary constitutes the surface separating partially mixed and partially melted zones [5, 10, 11].

The aim of this work was to identify the impact of the welding method of the boiler pipes made from P235GH and 16Mo3 steels on the microstructure and chemical composition of substrates and coatings.

## 2. Material and experimental procedure

The investigations were carried out on boiler pipes weld overlaid with Inconel 625 by four different suppliers designated as A, B, C and D. Pipes A, B and D were made from P235GH steel, while pipe C was made from 16Mo3 steel. The chemical composition of the P235GH and 16Mo3 steels is presented in Table 1. The basic difference in chemical composition of the steels is that P235GH is a non-alloy steel, while 16Mo3 contains approximately 0.3 % Mo. The carbon content in both steels was similar. Pipes A, C and D were clad by the CMT technique. Pipe B was clad by the GMAW technique followed by remelting of the surface layer of the deposited coating by the GTAW method. The chemical composition of the Inconel 625 wire used for coatings is presented in Table 2.

The microstructural examinations were performed on longitudinal cross-sectioned samples by means of light (LM, Axio Imager MAT. M1m Carl Zeiss) and scanning electron microscopy (SEM, Hitachi S – 3500N). The samples were subjected to two-stage etching: steel was etched in 2 % solution of nitric acid in $C_2H_5OH$ and after that the coating was electrolytically etched in a 10 % water solution of $CrO_3$ at a preset voltage of 2 V. The thickness measurements, ten for each sample, were carried on longitudinal cross-sectioned samples.

The qualitative and quantitative chemical composition analyses on metallograpic samples were determined by means of EDS in SEM. The quantitative analysis was aimed at identifying variations in the content of elements along the direction perpendicular to the fusion boundary. The EDS measurements were performed on a square-shaped area with a side of 60 μm. Such a methodology allowed for finding a macro composition of the coating independent of its microstructural inhomogeneity. Successive measurements were spaced every 0.3 mm. Since the width of the partially mixed zone usually extends from over ten to several dozen μm, a spot analysis in the vicinity of the fusion boundary was also performed. This allowed for the precise determination of the Fe distribution in this zone. The first point in the analysis was chosen in the base material at the distance of several μm from the fusion boundary. Successive measurements were per-

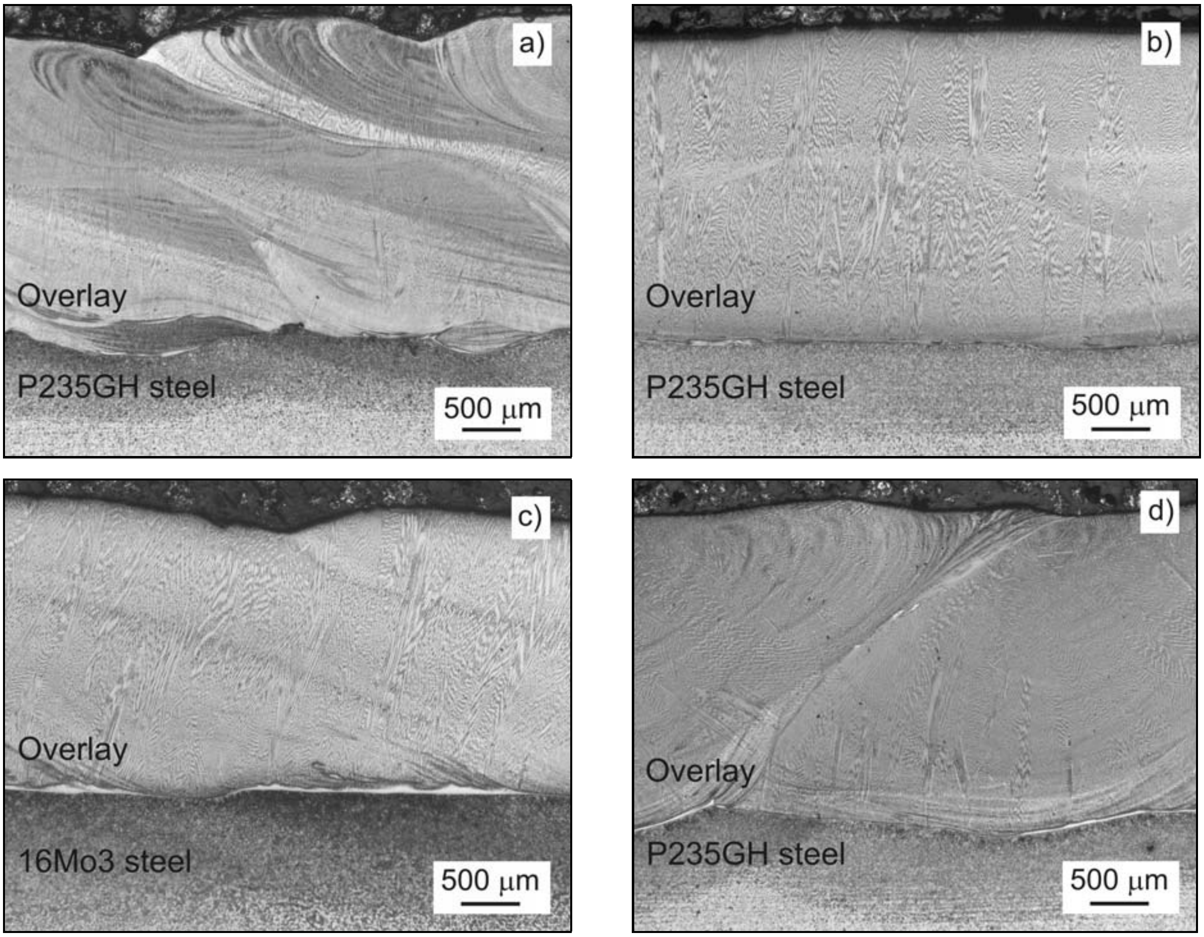


Fig. 2. Macrostructure of the Inconel 625 weld overlay: pipe A (a), pipe B (b), pipe C (c), pipe D (d).

formed every few μm. The content of all elements subjected to the analysis totaled 100 %. For each pipe the acquired results were collected on the diagrams showing the dependence of the elements content (wt.%) on the distance from the fusion boundary. Moreover, linear analyses of the chemical content of Ni, Cr, Mo, Nb and Fe were performed for the cross-section of the substrate and the coating.

## 3. Results and discussion

The microstructures of boiler pipes with the weld overlays are shown in Fig. 2. The investigations showed that all pipes were weld-overlaid by singular passes. The average thicknesses of the clad coatings were: A – 2.5 mm, B – 2.4 mm, C – 2.3 mm and D – 2.5 mm. The overlays produced by CMT differed in the bead slope. The average bead slope on pipes A and C was about 20°, while on pipe D – about 40°.

The following zones can be clearly distinguished on pipes cross-sections: fusion zone, non-etched partially mixed zone, heat affected zone, as well as the base material. The microstructure of boiler pipe D with the characteristic zones is shown in Fig. 3. The partially fused zone was not revealed on any investigated samples. The microstructure of the overlays was composed of dendrites with arms parallel to the direction of the heat flow. The microstructure in the heat-affected zone was composed of ferrite and bainite regardless of the implemented cladding method. On the other hand, the base material was characterized by the ferritic-pearlitic microstructure.

The quantitative analysis of the chemical composition performed in the areas of the fusion zone, the partially mixed zone and the base material, as well as linear analyses performed for particular weld overlays indicated that the non-etched zone on metallographic microsection may be a partially mixed zone. The chemical composition of this zone clearly differs from that of the base material and the overlay. The spectra from the partially-mixed zone show peaks generated by both Fe and the elements forming the overlay (Ni, Cr, Mo, Nb), however, their content is lower than the content of the same elements in the overlay and base materials (Fig. 3). The linear EDS analysis showed that the chemical composition of this zone varied from the composition of the fusion zone to the

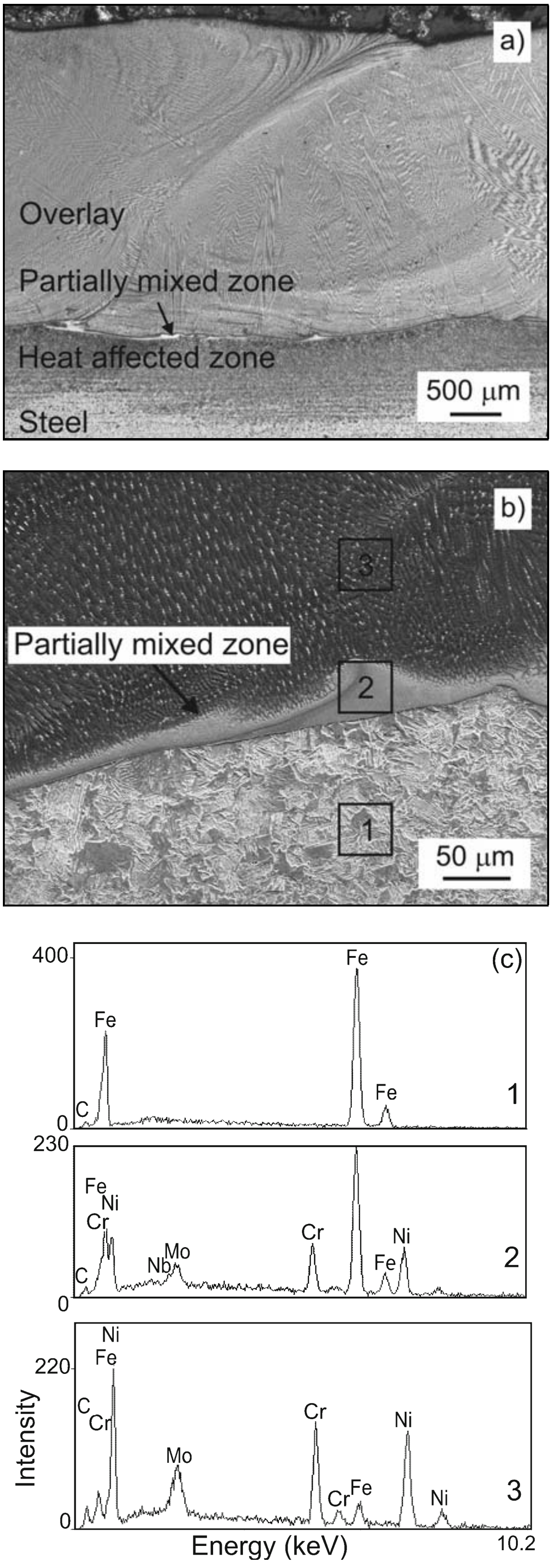


Fig. 3. Microstructure of the weld overlay with a marked partially mixed zone and the chemical analysis: light microscopy (a), scanning electron microscopy (b), EDS spectra from: 1 – base metal, 2 – partially mixed zone, 3 – overlay – pipe D (c).

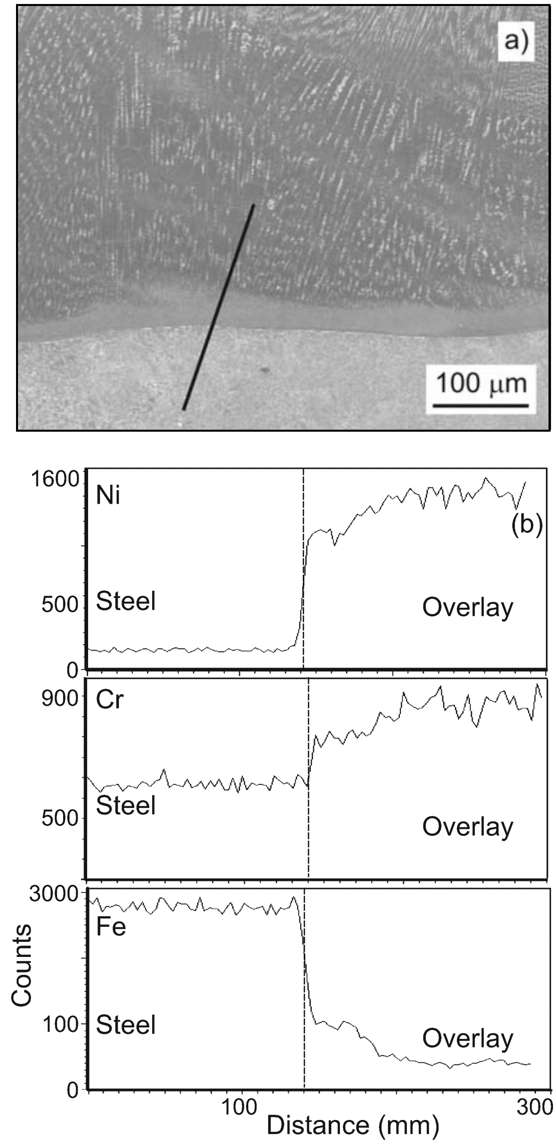


Fig. 4a,b. Linear distribution of the Ni, Cr, Fe on the cross section of the weld overlay – pipe D.

composition of the base material (Fig. 4).

The Fe content is clearly higher in the partially mixed zone than in the coating and decreases with the distance from the interface towards the coating surface. Also, the content of Ni, Cr, Mo and Nb is much lower than in the coating and it increases gradually with the distance from the interface. The thickness of the non-etched partially mixed zone of each welded overlay is within the range of several to tens μm. The EDS quantitative analysis performed on the cross-section of the base material and the coating showed that, regardless of the cladding method, the content of Fe in the deposited coating was higher than in the Inconel 625 wire used for deposition. The Fe content in Inconel 625 used for overlaying was about 0.3 %, while the Fe content for particular coatings adjacent

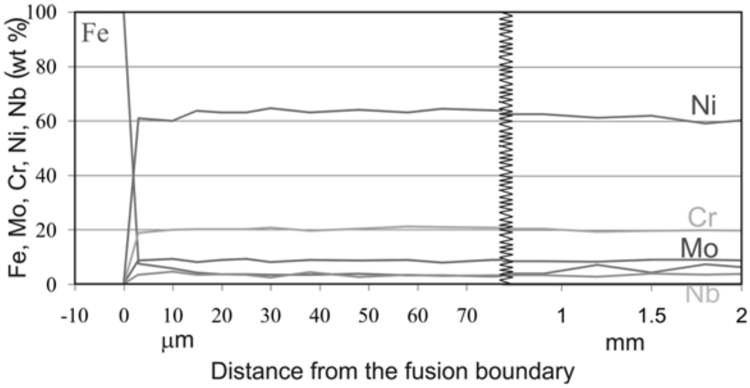


Fig. 5. Distribution of Fe, Ni, Cr, Mo, Nb (wt.%) depending on the distance from the fusion boundary – pipe A.

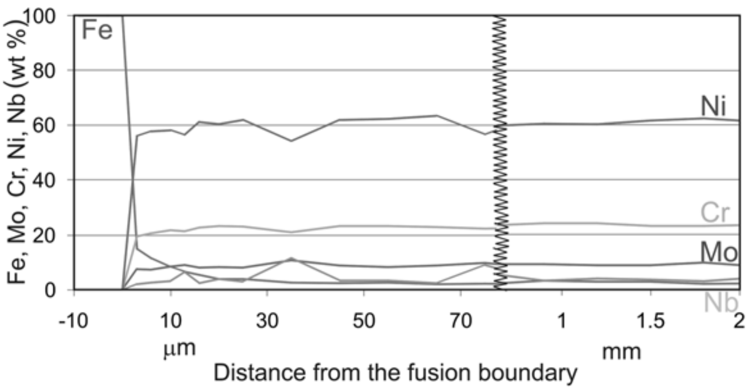


Fig. 6. Distribution of Fe, Ni, Cr, Mo, Nb (wt.%) as a function of the distance from the fusion boundary – pipe B.

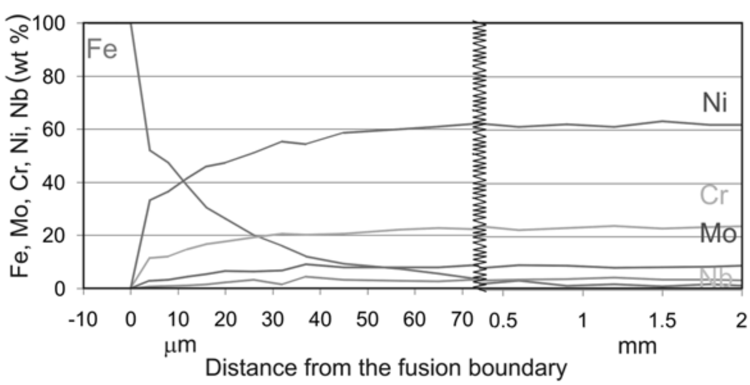


Fig. 7. Distribution of Fe, Ni, Cr, Mo, Nb (wt.%) as a function of the distance from the fusion boundary – pipe C.

to the surface (about 2.3 mm away from the fusion boundary for pipes A, B and D and about 2.1 mm for pipe C) were: for A – 5.5 %, B – 1.9 %, C – 1.1 %, D – 3.0 %. Figures 5–8 show exemplary distributions of Fe and other elements over the cross-section of the base material and the coating for pipes A, B, C and D, respectively. The higher Fe content in the partially mixed zone and in the coating results from the weld penetration and melting of the base material.

For the smaller bead slope (20°, weld overlay A and C) the Fe content decreases faster along the distance from the fusion boundary towards the weld overlay surface, compared to the weld overlay on pipe D, where the bead slope is 40° (Fig. 6). Also, in the weld overlay on pipe C, with a bead slope of 20°, the content of Fe decreases faster than in the remaining coatings due to an even fusion boundary, however, its value remains at a low level until the coating surface is reached. In the weld overlay on pipe A, in spite of a fast decrease of the Fe content, the Fe content close to the weld overlay surface is high, due to an uneven fusion bound-

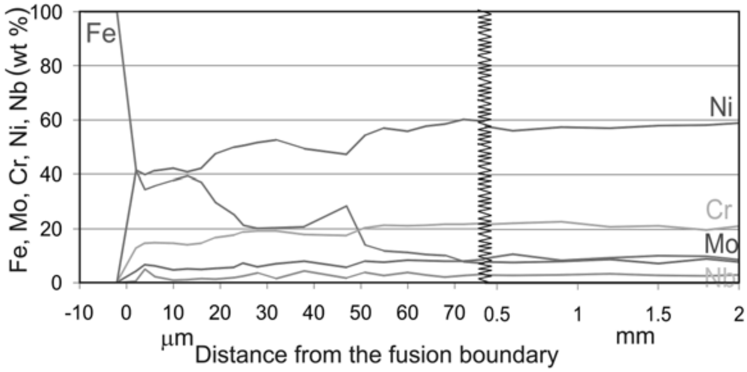


Fig. 8. Distribution of Fe, Ni, Cr, Mo, Nb (wt.%) as a function of the distance from the fusion boundary – pipe D.

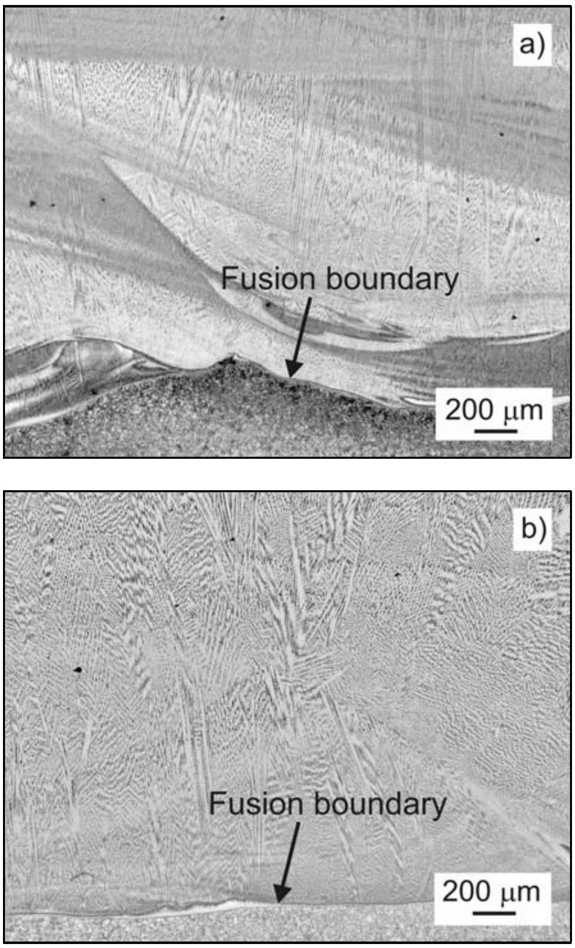


Fig. 9. The fusion boundary of the weld overlay: pipe A (a), pipe B (b).

ary and numerous smudges on the substrate material.

The highest Fe content close to the surface was identified in weld overlays on pipes A and D. These weld overlays simultaneously exhibited the least uniform fusion boundary and the least smooth external surface. The surfaces of the weld overlays on pipes C and B overlaid by the GMAW method and fused by the GTAW method – where the Fe content at the coating interface is the lowest – have a more uniform fusion boundary. The most uniform external surface is identified in the coating deposited by GMAW and subsequently fused by the GTAW method (weld overlay on pipe B). The non uniform fusion boundary of the weld overlay A and the more uniform surface of the weld overlay B are presented in Fig. 9. The smoothness of the surface after welding, important from the corrosive point of view, is affected primarily by the degree of overlapping of the successive beads, the bead slope and the shape of the cross-section of a single bead.

## 4. Conclusions

– Regardless of the welding method, the overlays consisted of the following microstructural zones: fusion zone, partially mixed zone, partially melted zone and heat-affected zone.

– The Fe content is clearly higher in the partially mixed zone than in the fusion zone and decreases with the distance from the interface towards the coating surface.

– The lowest Fe content near the external surface of the coatings exhibited overlays possessing the most uniform fusion boundary and the smoothest external surface. The most uniform external surface was identified in the coating deposited by the GMAW and subsequently fused by the GTAW method.

### Acknowledgements

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