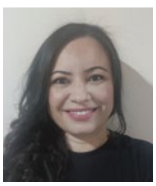
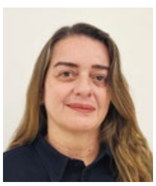
Laboratory Simulation and Characterization of Duplex Laying Head Pipes Thermal Distortions



Laying head pipes, used in wire rod rolling, may undergo distortion during fabrication with duplex stainless steel. Throughout hot forming, one part of the pipe is in contact with the metallic die, while the other is exposed to the environment. After laboratory simulations, it was concluded that differences in cooling patterns between the inner arc and the outer arc cause the distortion during the manufacturing process. Industrial trials to achieve a more homogeneous microstructure and prevent distortion have already been fully implemented and approved.

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Introduction

Wire rod is a hot-rolled product, usually produced in the form of coils and used as raw material for various critical components in the industry, including automobile springs, steel cables, agricultural machinery, construction materials, screws and welding electrodes, among others. These materials need to be manufactured with high demands for quality, mechanical strength and structural integrity. To meet these requirements, high-performance equipment must be used in wire rod manufacturing.[1]

Laying head pipes are commonly used to modify the wire rod's geometry from a straight longitudinal section to an Archimedean helix at speeds up to 125 m/second. This high-speed transformation enables the formation of coils in different dimensions, optimizing the storage and transportation of the product. Fig. 1 illustrates the formation of the wire rod coil in the laying head. The application of laying head pipes for coil formation after finishing rolling is also crucial for effective air cooling to achieve the desired final properties of the wire, in which different materials and dimensions of laying head pipes influence the spiral formation.[2]

In the constant pursuit of the best quality and cost-benefit ratio for every process and product, the market is continually evolving to ensure the required quality. The wire rod mill, being a critical component in the production chain, is influenced by multiple factors such as equipment quality, calibration and parameters, directly affecting the quality of the final product: the wire rod. This, in turn, impacts the quality of screws, springs, electrodes, tire wire and, subsequently, other downstream products.

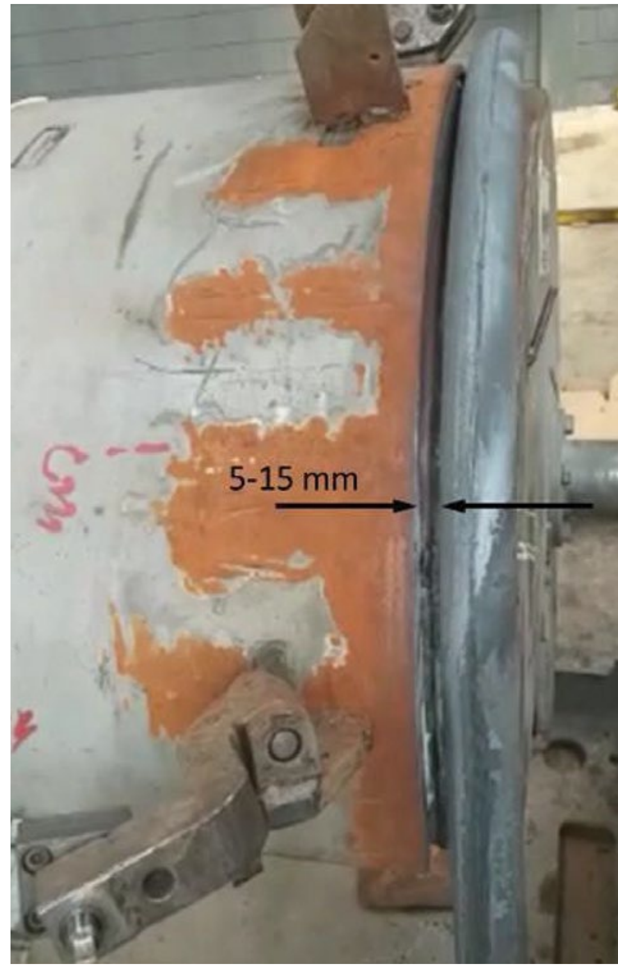
In the manufacturing of duplex stainless steel laying head pipes after hot forming and cooling in the steel bending machine/mold/die, it is common to encounter 5- to 15-mm axial and diameter distortions, which affect the geometry and, consequently, the quality of the laying head pipe because it is not according to the technical drawing. During the cooling process in the formation of the spiral pipe, a difference in the volumetric fractions of ferrite, δ, and austenite, γ, has the potential to generate a contraction difference between the outer and inner arcs (contact with the bending machine) of approximately: dL/L = 0.0005 (0.05%). Fig. 2 shows the laying head pipe spring effect assembled in die. To gain a better understanding of the reasons for the distortions and microstructural mechanisms of the process and

Figure 1

Wire rod coil in the laying head.

Figure 2

Axial and diameter laying head pipe distortions.



ensure product geometry, laboratory and field analyses at SMS group Brazil were conducted and successfully applied to the duplex stainless steel laying head pipe.

Discussion

Theoretical Laying Head Pipe Distortion Evaluation

To assess whether a contraction difference between the outer and inner (Fig. 3) curvatures of 0.05% would have the potential to produce the observed distortion, the simplified geometry of an open ring was considered, as shown in Figs. 4a and 4b. Following a contraction difference that results in the expansion of the inner arc compared to the outer one, the situation presented in Fig. 4c would occur: The opening β would emerge to maintain consistency $De' = Di' + 2 \cdot d'$, where $d' \cong d$.

Applying this simplified model to a ring with a 1,000-mm internal diameter and a pipe diameter of 50 mm, according to measurements of a laying head pipe, it was observed that a 0.05% difference in contraction could lead to an opening of 1.8° or 15.7 mm of arc. This value is expected to vary based on the fraction of transformed phase and the actual thermal cycle in each section of the coil former. Nevertheless, the model indicates that the calculated distortion is of the same order of magnitude as that observed in the actual process.

Figure 3

Laying head pipe section in the bending machine.

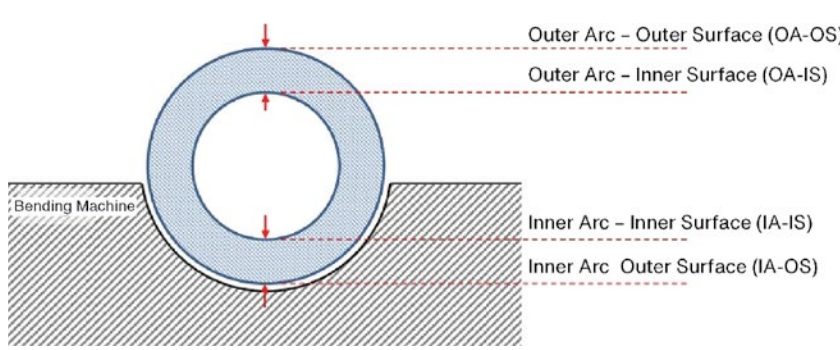
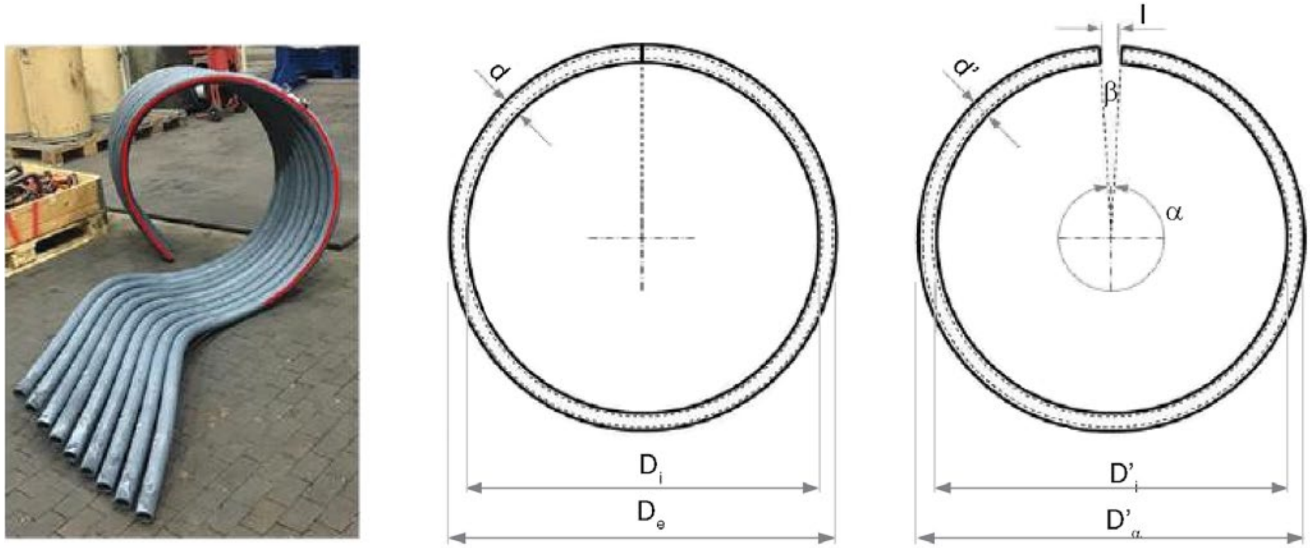


Figure 4

Simplified model for assessing the expansion of the inner arc in relation to the outer arc. De is the outer diameter; Di is the inner diameter; d is the rim diameter.



(a) (b) (c)

Dilatometry Simulation

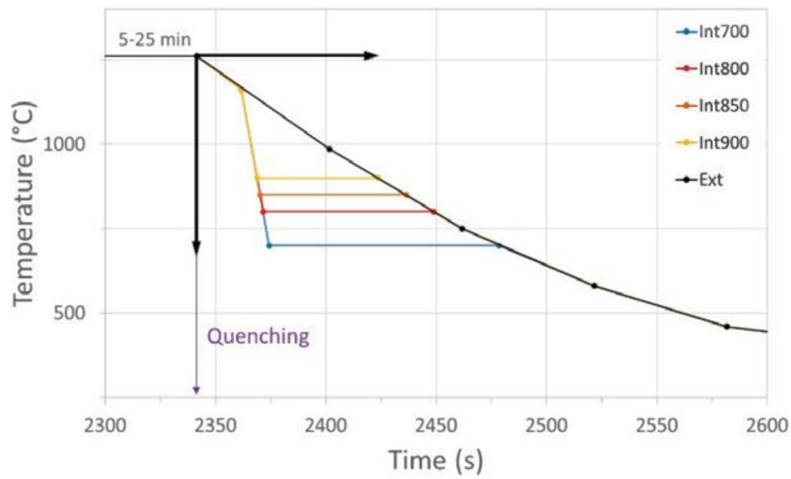
The thermal cycle of the external curvature of the laying head pipe during forming and cooling was characterized using an infrared camera along the pipe's length. As it was not feasible to measure the thermal cycle on the inner curvature, the part of the pipe primarily cooled by the matrix was considered. It was assumed that from the moment the pipe begins forming, a faster cooling rate is imposed by contact with the metal matrix, and heat propagation by conduction. Subsequently, with the heating of the matrix and a decrease in contact pressure, the cooling rate would decrease (simulated by an isothermal plateau). Finally, with the introduction of forced cooling after laying head pipe forming, the cooling rate on the inner surface increases again. Due to the challenge of precisely determining the thermal cycle on the inner curvature, simulations were initially performed with isothermal plateaus at 700, 800, 850 and 900°C, as shown in Fig. 5a.[3,4]

Figs. 5b and 5c show the dilatometry curves starting from reheating temperature and soaking time of 5 and 25 minutes. By taking the curve of outer arc as reference (black), it can be seen that the inner arc contracts or expands depending on the plateau temperature considered. Fig. 6 summarizes these results. It shows the length variations observed in the internal arc cycles in relation to the external arc cycle, for both soaking times studied. There is a trend for greater expansion near 800°C and, on the other hand, at lower (700°C) or higher (850 and 900°C) temperatures these variations decrease, which may even indicate contraction of the internal arc in relation to the external arc. It is possible that the isothermal plateau at higher temperatures (850 and 900°C) brings together both thermodynamic driving forces and sufficient kinetic to promote the transformation of a greater volume fraction of ferrite (δ) into austenite (γ), producing contraction in relation to the outer arc. At a lower temperature (700°C), kinetics becomes an obstacle, even with a high thermodynamic driving force. This behavior is expected metallurgically, since the transformation of ferrite into austenite is a thermally activated phenomenon and therefore dependent on temperature and time (in this case, represented by the variation in length, which is a function of time at the isothermal plateau).

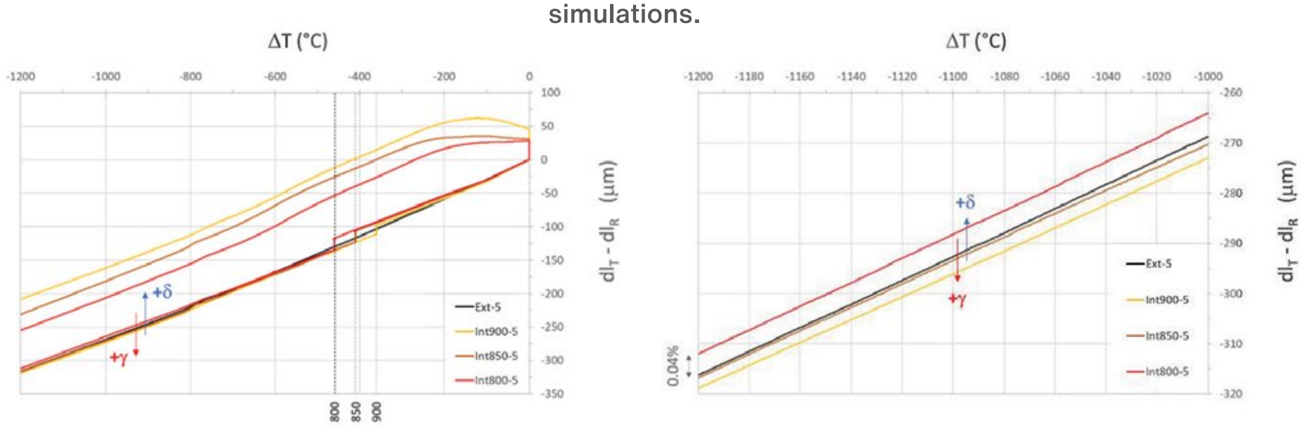
The samples simulated by dilatometry were characterized using x-ray diffraction (XRD) to assess the correlation between length variations and the relative fractions of ferrite and austenite. The results indicate that, initially, at the soaking temperature, the sample exhibits 78% ferrite and only 22% austenite, obtained after characterization of sample quenched from this temperature (Fig. 5a). During cooling, the ferrite undergoes transformation into austenite, with the amount depending on the applied thermal cycle. After cooling, the sample simulating the outer arc shows a significant increase in the austenite fraction, changing from 22% to 52%. On the other hand, samples from the inner arc, in contact with the bending machine, exhibit lesser phase transformations from ferrite to austenite: From 22% to 35% at the 700°C isotherm, from 22% to 49% at the 800°C isotherm, and from 22% to 45% at the 900°C isotherm. These results suggest that the expansion of the inner arc relative to the

Figure 5

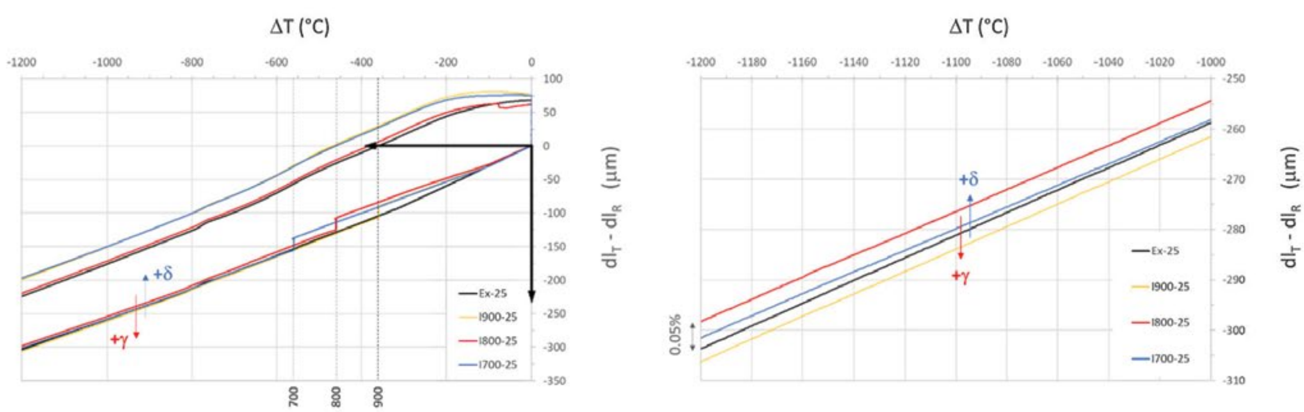
Thermal cycles for the dilatometry simulation and curves starting from soaking temperature.



(a)
Thermal cycles for the dilatometry simulations.



(b)
5-minute soaking time.

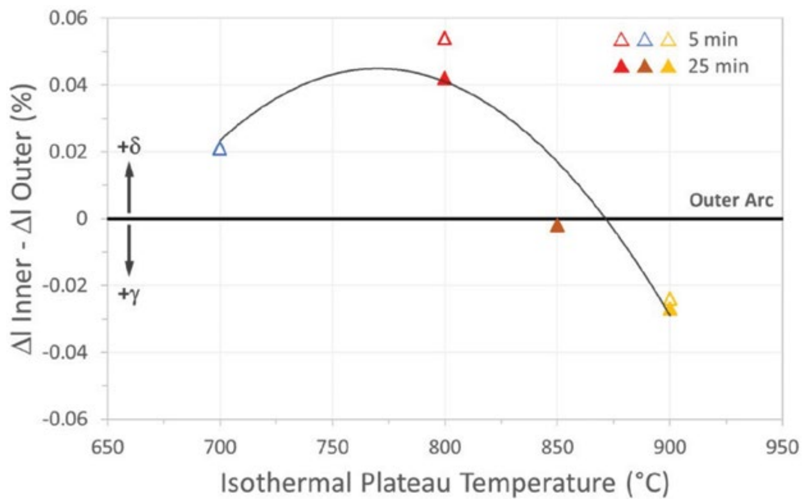


(c)
25-minute soaking time.

outer arc, observed under laboratory conditions, is justified regardless of the chosen thermal cycle to represent the cooling of the inner arc (700°C, 800°C or 900°C isotherm), as austenite has a smaller volume than ferrite.

Figure 6

Summary of length variations in relation to external arc simulations, for 5 and 25 minutes of soaking.



Laying Head Pipe Microstructure Analyses

Samples for XRD and optical microscopy (OM) were taken from the industrially formed duplex stainless steel laying head pipe at positions indicated in Fig. 3. The fractions of ferrite and austenite for each of the four samples are presented in Fig. 7. Microstructure examples for each sample are shown in Fig. 8. It is observed that the sample from the region in contact with the matrix (IA-OS) exhibits a higher amount of ferrite (brown) than austenite (white), compared to the sample exposed to the environment (OA-OS), as shown in the dilatometry simulation. This results in a greater contraction of the external arc in relation to the internal arc or, in other words, a relative expansion of the internal arc compared to the external one. The difference in the quantification of phases by XRD on the inner surface (OA-IS and IA-IS) of the tube may be related to the banding effect caused by the partition during solidification, since the plane analyzed is perpendicular to the radial direction of the tube.

Laying Head Pipe Field Analyses

The results from dilatometry simulations and characterizations conducted on the curved duplex stainless steel pipe indicate the need to minimize temperature differences between the external and internal arcs. In a simplified manner, there are two ways to achieve this goal:

1. By decreasing the cooling rate of the internal arc.
2. By increasing the cooling rate of the external arc during the initial moments of the bending process.

The second way is technically more practical, but has to be done from the moment the pipe contacts the die until approximately 700°C. Below this temperature, the effects would not be significant, as the temperature differences are smaller, and the transformation of ferrite into austenite occurs at a slower rate. In this approach, the transformation from ferrite to austenite would be more uniform, as the cooling rate would be consistent. This would help eliminate distortion and spring effects, ensuring a comparable distribution of each phase in both the outer and inner arcs. This approach was field tested at SMS group Brazil yielding positive results.

Figure 7

X-ray diffraction and optical microscope results for the samples taken at the positions indicated in Fig. 3.

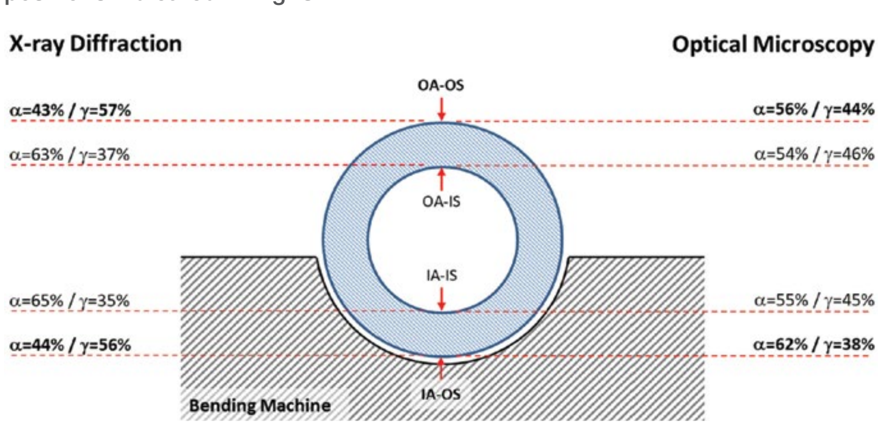
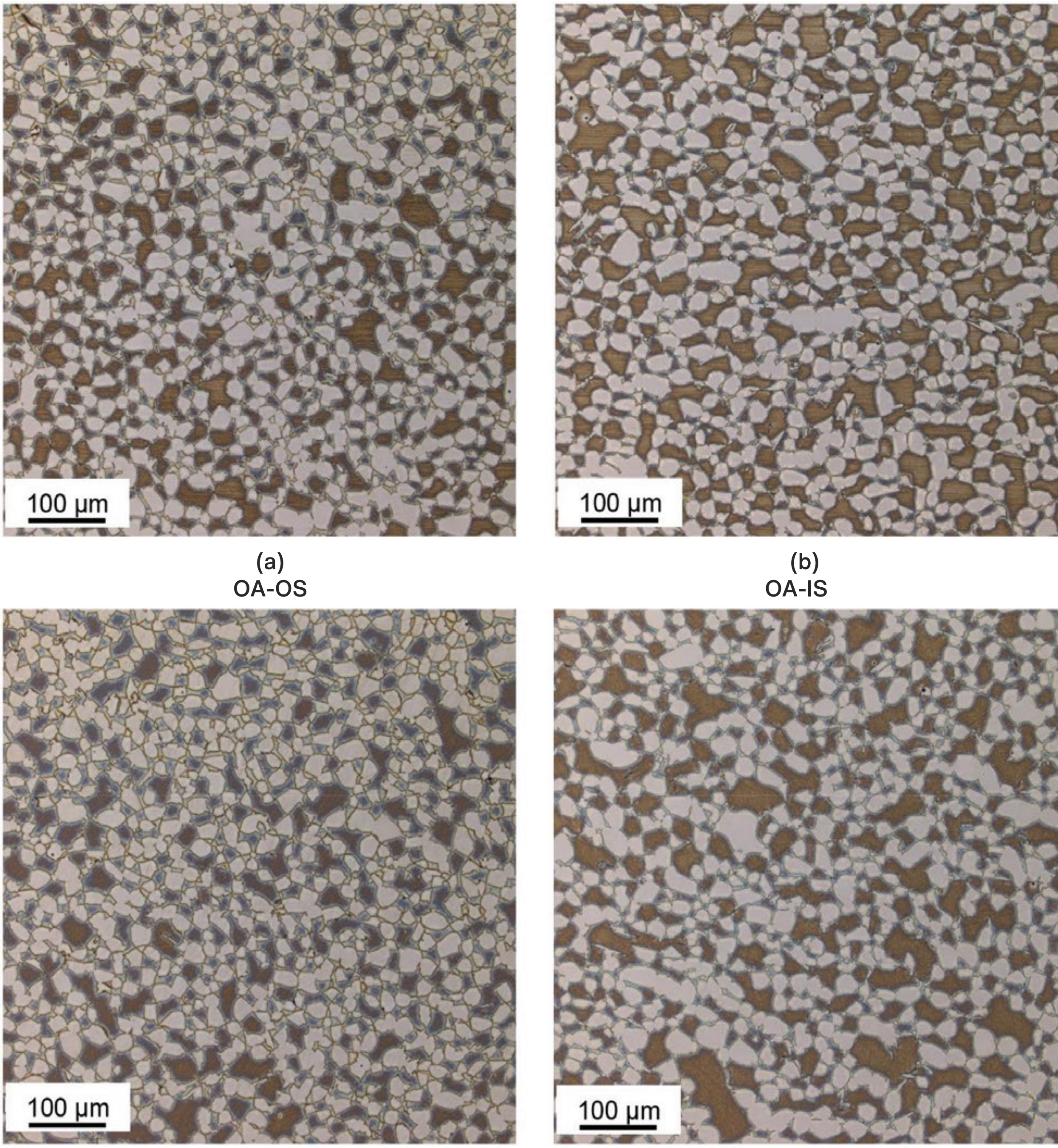


Figure 8

Microstructure for the samples taken at the positions indicated in Fig. 3 (Electrolytic etching with a 10% NaOH solution). (a-b) Outer Arc; (c-d) Inner Arc. Brown phase: ferrite; White phase: austenite.



(a)
OA-OS

(b)
OA-IS

(c)
IA-OS

(d)
IA-IS

Conclusions

The presented results allow for the conclusion that differences in the laying head pipe cooling pattern between the inner arc (in contact with the matrix) and the outer arc (exposed to the environment) are responsible for the distortion observed in the industrial process. This variation in the cooling profile results, at the end of the process, in different relative fractions of ferrite and austenite. A greater transformation of ferrite into austenite is observed in the outer arc as a consequence of slower cooling at the beginning of the bending process. With more austenite, the outer arc contracts in relation to the inner arc, producing the observed "opening"/spring effect. The same can be inferred for the distortion component in the axial direction of the machine, given that the channel is asymmetric. The solution to the distortion problem involves minimizing the temperature differences between the outer and inner arcs of the laying head pipe bending machine. It successfully underwent field testing and obtained approval at SMS group Brazil.

This article is available online at AIST.org for 30 days following publication.

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