Outside diameter growth prediction in quenching seamless pipes of low carbon steel

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INTRODUCTION

Heat treatment is an important seamless pipe production step to enhance the quality of final product such as mechanical strength, hardness and dimensional accuracy. Quenching is one of the most critical stages throughout the heat treatment. As the material cools, thermo-physical and metallurgical properties vary, causing the development of thermal stresses and geometric distortions [1]. Generally, at the beginning of the quenching process there is a completely austenitic structure which will become pearlite, ferrite, bainite, or martensite due both to the cooling rates applied as well and to the chemical composition of the steel. As a result, this stage of the process determines the final microstructures and mechanical properties of the steel and it is usually followed by tempering.

Industrial quenching control is complex since it involves various factors such as: phase transformations, the quenching medium, and the severity and uniformity of the cooling, which can influence the final dimensions of the treated component, favoring undesirable geometrical distortions [2, 4]. Moreover, there are other variables in the process which interact with one another in different ways; hence, distortions cannot be easily estimated.

The final diameter prediction of the seamless steel pipe, considering the process and product parameters as input data, permits the reduction of tests and reworking within the industrial production situation. Within such context, investigations have been performed focusing on the distortions caused by quenching. There is, then, an industrial demand intrinsically related to the use of computer technology applied to engineering, also known as Computer Assisted/Aided Engineering, focusing on optimizing all processes of production and efficiency related to the lifespan of tools, saving project time, and consequently diminishing costs. In this way, industrial projects can be developed in short term when compared to projects which do not have the utilization of computational tools, and experimental tests can be better planned and aligned with the objectives and predictions based on a previous modeling [5].

The numerical simulations of microstructure predictions and residual stresses have been useful for the understanding of the steel distortion mechanisms. The time sequence of the phase transformation and of the distribution of the thermal tensions is the main investigated targets [6, 7, 8]. For the last forty years, many models have been developed and amongst them there is a model which estimates the temperature profile which includes the latent heat of transformation and a model in finite elements in order to calculate the residual stresses as well as deformations [9]. In 2006, a research was conducted in the attempt of explaining the origin of the distortion and of the residual stresses in quenched cylinders by using a method of analysis which encompasses phase transformation models, by resorting to the finite elements method [10].

The existing results indicate the importance of quantitatively precise knowledge of the thermal, mechanical and metallurgical parameters involved in the stresses generation under various cooling conditions. The awareness of such variables as well as their interactions allow the optimization of the quenching process, the microstructure of the material and the consequent mechanical properties.

Quenching by immersion in tanks is one of the most used process to obtain martensitic and bainitic structures in steels [7]. Direct quenching by immersion refers to the cooling process of the piece from the austenitization temperature down to room temperature by immersion in liquids that vaporize. Oil solutions, water and watery solutions of polymers are frequently used. In the present case, the quenching medium is just water. In addition to this quenching process, there are other quenching methods used in the production of seamless pipes, such as ring quenching and the spray quenching.

The present industrial quenching process of seamless steel pipes in the water tank consists of immersing the pipe at a temperature of about 900°C in a tank with water at a temperature of 25°C. The pipe is withdrawn from the tank at a temperature lower than M_f (martensite finish temperature).

The actual industrial scenario requires seamless pipe production within the strict dimensional specifications of the APIs, such as specific requirements for external diameter, ovality and straightness. Numerical simulation is a great method of approaching quenching distortion [8]. However, there is no satisfactorily comparison of numerical simulation and experimental results of distortions for seamless steel pipes in the literature.

The present paper presents a methodology to predict the outside diameter growth of a low carbon steel seamless pipe after the industrial tank quenching using simulations based on the finite element method. The specific objectives are presented as follows:

- to obtain the cooling curves of a steel pipe in order to calculate the heat transfer coefficient;
- to simulate the pipe outside diameter growth and compare it with industrial results.

MATERIAL

A low carbon steel with chemical composition range shown at table 1 was used in the present simulations of the outside diameter distortion after tank quenching. This steel has a good hardenability, and it is used to produce steel seamless pipes in a large range of yield strength, between 552MPa and 965MPa. The nominal sizes are: 244.48mm outside diameter, 11.99mm wall thickness, and 12m length.

Table 1. Chemical composition range of steel (in wt. %) [11]

C		**Mn**		**Ni**	**Cu**	**P**	**S**	**Si**
Min.	Max.	Min.	Max.	Max.	Max.	Max.	Max.	Max.
-	0.43	-	1.90	0.25	0.35	0.030	0.030	0.45

Thermo-physical and metallurgical properties

To obtain material properties data for the simulation, JMatPro (Sente Software Ltd., UK) software was used. The thermo-physical and mechanical properties for each phase were taken into account. For heat treatment distortion simulations in an elasto-plastic mode, the following properties have to be used: Young’s modulus, Poisson´s modulus and the flow stress curve. For the thermal dilatation and contraction – elastic properties, the thermal expansion coefficient for each steel phase were considered. The volumetric expansion coefficient associated with the austenite decomposition in martensite during quenching that depends on the carbon content [12] was utilized. The phase transformation kinetics TTT/CCTdiagrams, were obtained from JMatPro.

Piecework dimensions were affected by the presence of an applied stress during the transformation, as if the material had been subject to plastic deformation. This effect is referred to as transformation plasticity which occurs even at low stresses below the yield stress of the material [13]. In some studies the transformation plasticity has significantly influence the stress-strain distributions and the distortion [13-14]. This phenomenon was considered in the distortion simulations.

In order to consider the heat transfer modelling in the pipe, the following properties were taken into account: thermal conductivity, specific heat, density and latent heat due to the phase transformation per time and volume unit. The latent heat accounts for the net energy gain or loss when a phase change occurs which could affect the cooling rate during quenching.

Experimental procedure to obtain the cooling curves

A pipe with the same chemical composition presented at Table 1 was used in order to measure the cooling curves. This pipe has a 244.48mm outside diameter, 11.99mm wall thickness and 12m length.

The pipe temperatures were measured by nine thermocouples type K fixed in different pipe locations: radial (from R1 to R3) and axial (from L1 to L3), according to Figure 1. These temperatures were recorded during the quenching process. Table 2 describes other important parameters used for the quenching process in tank.

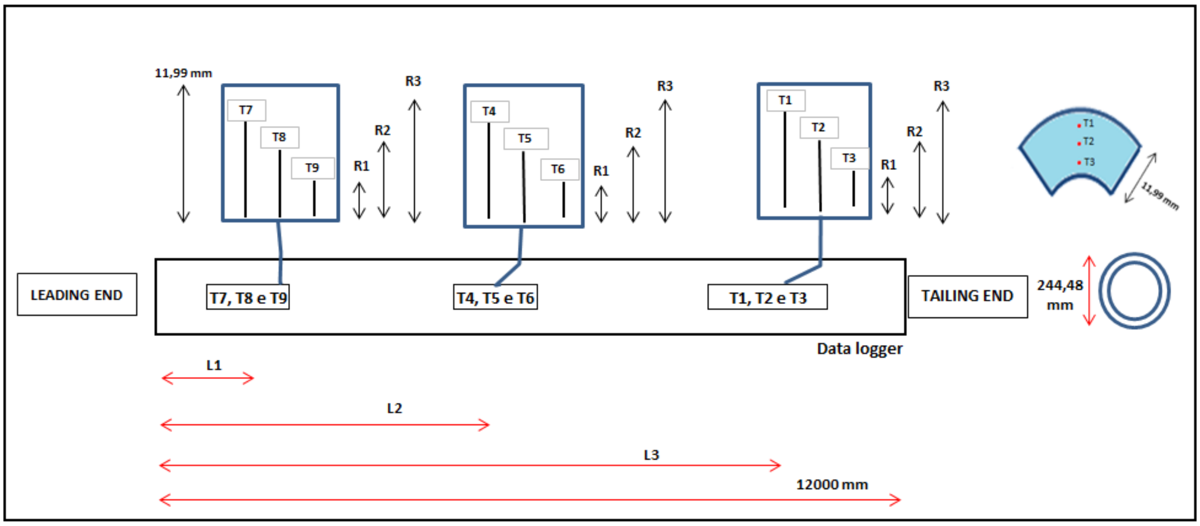


Figure 1 - Schematic pipe assembly used in experimental test

Table 2. Quenching conditions of thermal cycle

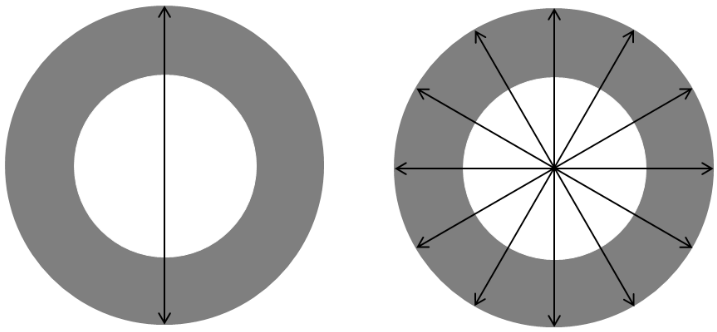
Parameters	Values
Total time of pipe at austenitizing furnace (min)	30 – 50
Pipe temperature after austenitizing furnace (°C)	T_a
Pipe temperature before quenching (°C)	T_b
Immersion time (s)	t_e
Opening time of internal jet (s)	t_i
Turning rolls speed (RPM)	N
Water flow – internal jet (m^3/h)	Max
Water temperature (°C)	25
Pipe temperature after quenching (°C)	T_c

The assembled pipe (with thermocouples) together with a data logger (to record the temperatures and time) were charged into the austenitizing furnace to be heated until the initial test temperature (T_a). After the austenitizing process, the pipe was transported to the turning rolls where the immersion in the tank will initiate. The turning rolls spin with a specific speed (N). Before the immersion, the pipe temperature (T_b) must be above the critical temperature AC3 (critical temperature to obtain 100% austenite). During quenching, the instant (t_i) to open the internal jet was defined. The pipe was quenched until the immersion time (t_e) was equal to the target. After the quenching, the final pipe temperature (T_c) was to be measured in order to assure the pipe temperature was below the Mf temperature (temperature to obtain 100% of martensite).

Actual measurements of pipe out diameter

The simulations were validated with actual measurements obtained in the industrial data. The initial out diameter was obtained by pipe as rolled and it is measured by Zumbach equipment. The pipe as quenched was measured IMS OD Machine at the heat treatment line.

The Zumbach equipment measured one point of out diameter and OD machine measured twelve points, according the figure 2.



(a) (b)

Figure 2 – Out diameter equipment's (a) Example of Zumbach measurements (b) Example of IMS OD Machine measurements

Numerical simulation of pipe outside diameter distortion

The numerical simulations of the outside diameter growth were performed using Deform2D-HT, v11.1 (SFTC, Columbus, USA). This module solves non-linear problems depending on time based on the finite element method (FEM). The material properties calculated by JMatPro were inserted into the software. Boundary conditions were defined to simulate the outside diameter distortion of the pipe and they were applied to the Deform2D-HT. Table 3 shows the FE setup.

Table 3. Boundary conditions for numerical distortion simulation

Operation	Parameters	Values
Heating	Code	Deform2D-HT
	Geometry	Axisymmetric
	Material	Calculated by JMatPro
	Initial temperature (°C)	20
	Final temperature (°C)	850
	Object	Elastic
Tank quenching using water	Code	Deform2D-HT
	Geometry	Axisymmetric
	Material	Calculated by JMatPro
	Initial temperature (°C)	850
	Heat Transfer Coefficient (HTC)	Function of temperature
	Water temperature (°C)	25
	Object	Elasto-plastic

The heat transfer coefficient was obtained from the cooling curves using the inverse module at DEFORM2D-HT, v11.1 (SFTC, Columbus, USA). The time increment was 0.01s and the stopping condition was the immersion time in the tank quenching. The simulated results were validated by outside diameter measurements of the pipe in the industrial area before and after the quenching process.

RESULTS

Some variables in the graphs are represented by relative values, *i.e.*, the presented values are divided by the maximum measured value obtained for that specific variable.

Experimental cooling curves

The cooling curves for two positions on pipe were evaluated: the leading end – close to the internal nozzle and the tailing end. These positions are shown in Figure 3. The thermocouples broke at the middle position of the pipe length, so it was not possible to obtain these temperature measurements.

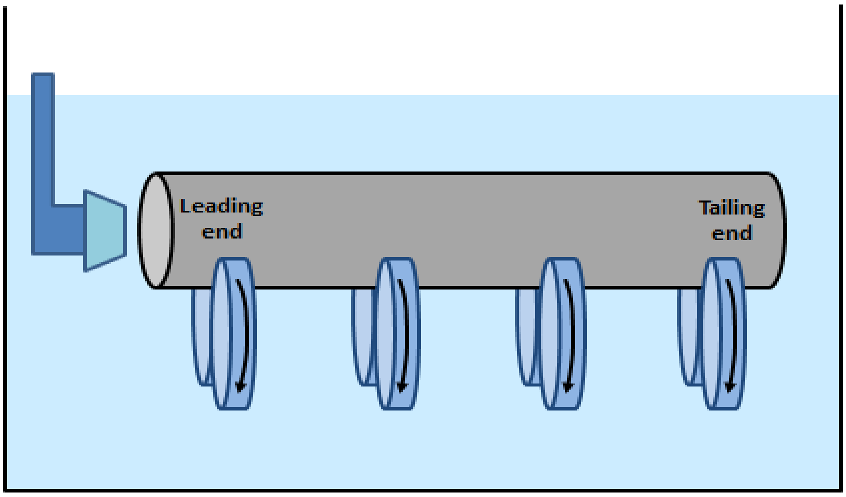
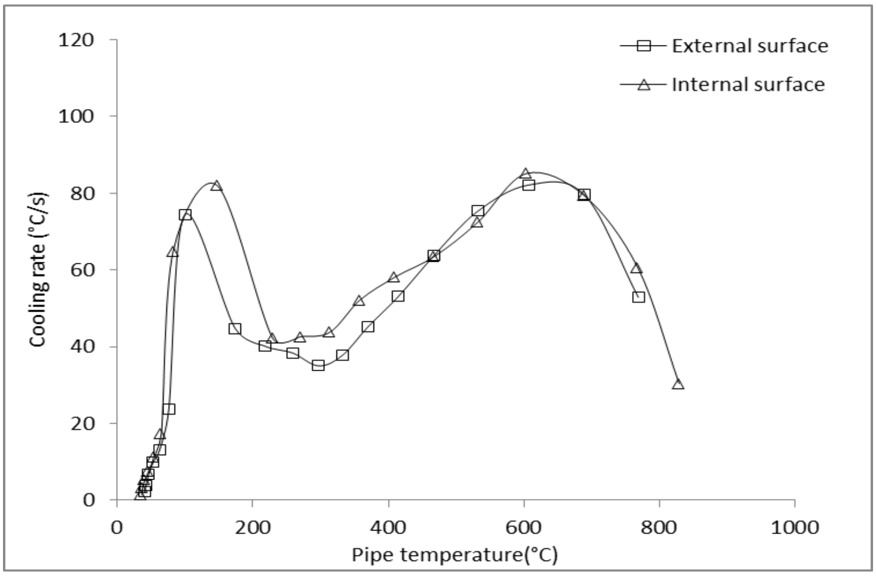


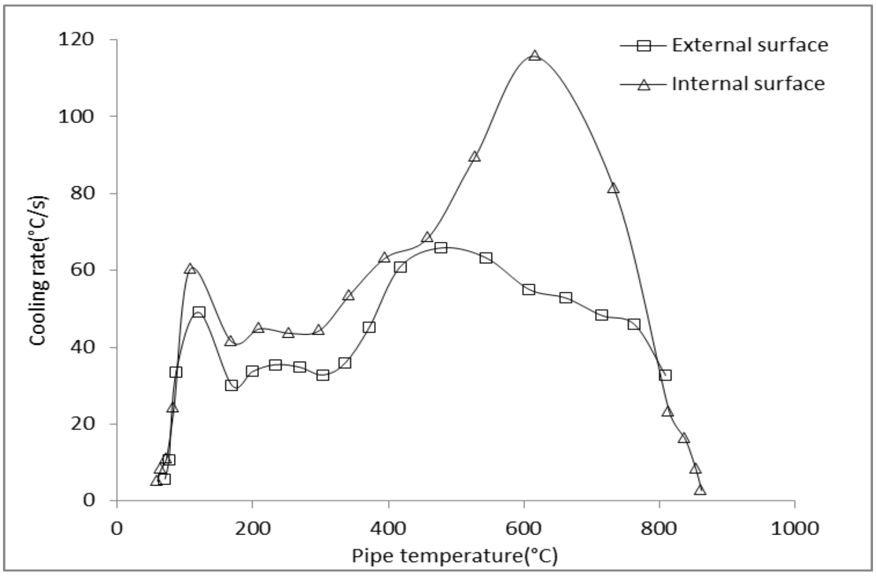
Figure 3 – Pipe positions for measuring the cooling curves into the quench tank.

Figure 4 presents the cooling rates measured by thermocouples 7 and 9 on the leading-end and thermocouples 1 and 3 on the tailing-end, according to the schematics shown in Figure 1. Figure 4a shows the cooling rates obtained along the wall thickness at internal and external surfaces for leading end position. The external surface cooling rate is similar to the internal surface cooling rate from 900°C until 460°C. This instant corresponds to the time that the internal jet reaches the maximum water flow. After this moment, the water cooling rate at the internal surface is higher than the external part due to the internal jet.

For tailing end pipe (Figure 4b), the cooling rate of internal surface was higher than the ones at the external surface during all quenching process. This difference was not expected, but it is necessary to investigate with additional tests to verify the measurement repeatability in detail.



(a)



(b)

Figure 4 – Cooling rate during the quenching process at: (a) leading end and (b) tailing end.

Pipe distortion simulation and comparison with the actual measurements

A simulation of the outside diameter (OD) growth of the pipe leading end was conducted using Deform2D-HT, applying the boundary conditions shown in Table 3. This pipe leading end location was chosen due to its higher cooling rates and cooling heterogeneity when compared to the tailing end location. The outside diameter growth was taken based on the as rolled diameter.

Predicting the final outside diameter by a FE model, the result was close to the measured value. The simulated outside diameter behavior during the cooling operation is shown in the Figure 5. The final simulated value of the outside diameter distortion was very close to the experimental one. There was a good agreement between simulated and measured outside diameter distortion: in this case the out diameter distortion was 0.15%, and the measured value was 0.13%: there was only a difference of 0.02% between measured (0.13%) and calculated (0.15%) outside diameter growth value after the quenching process.

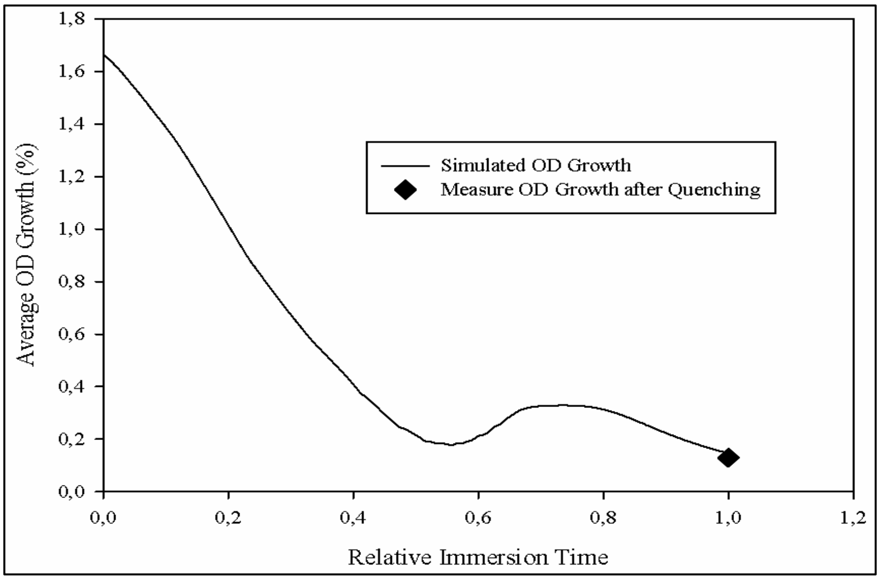


Figure 5 – Simulated outside diameter growth behavior at the leading end during quenching process.

It can be observed from the out diameter behavior in Figure 5 that it decreases with the temperature decreasing, but increases again around 0.5 relative immersion time. At that instance, the average volumetric fraction of martensite reaches about 40% in the pipe wall thickness, as shown by Figure 6.

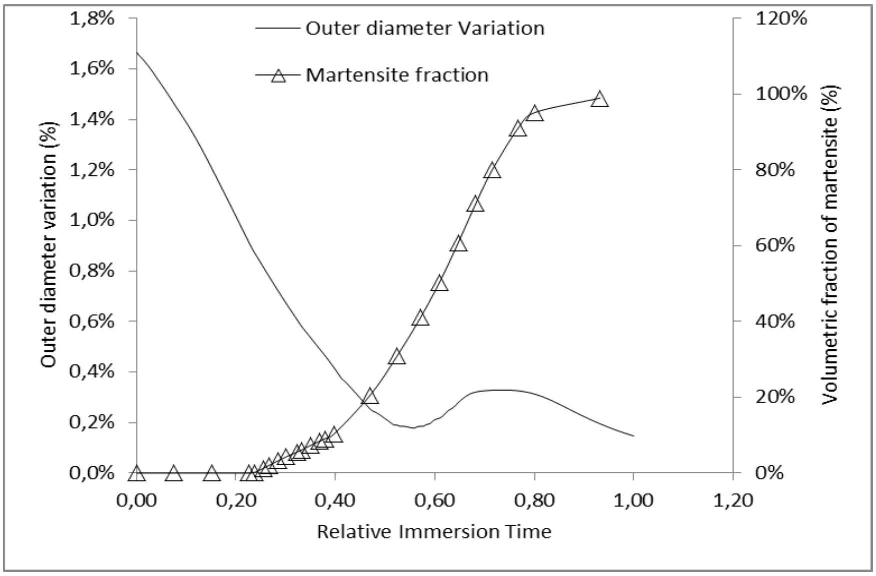


Figure 6 – Martensite volumetric fraction distribution along the pipe wall thickness during tank quenching

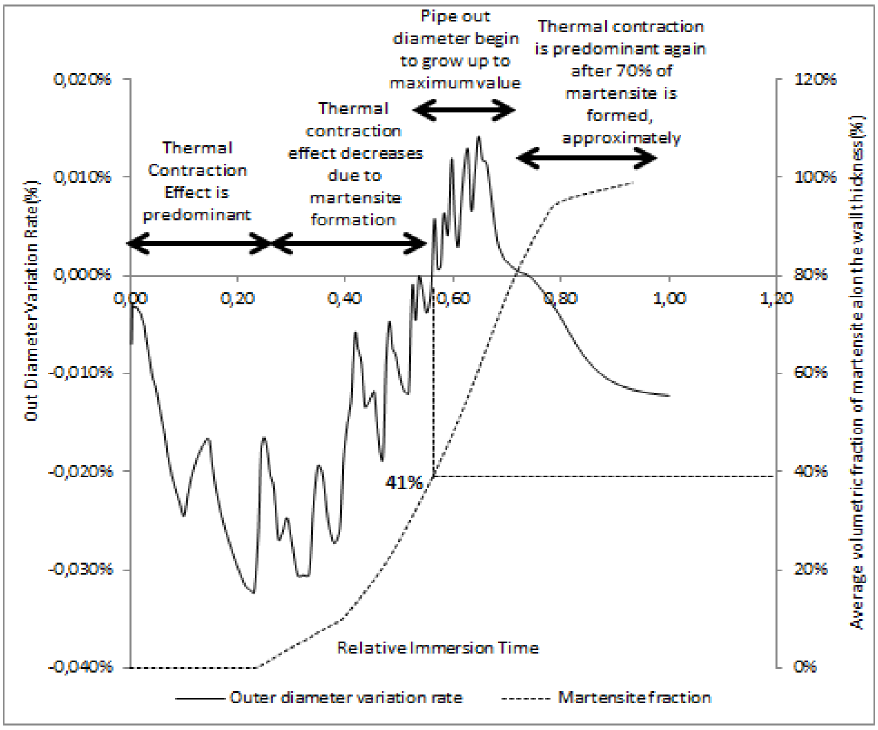


Figure 7 – Outside diameter variation and volumetric fraction of martensite distribution along the wall thickness.

Figure 7 shows the out diameter variation and volumetric fraction of martensite along the wall thickness during the quenching process. In this case, it was verified the thermal contraction effect and the martensite formation. The negative values of the out diameter variation corresponds to the out diameter reduction due to the thermal contraction and positive cooling rates are related to the out diameter growth due to volumetric changes caused by decomposition of austenite to martensite. The first seconds of immersion in tank, the predominant physical process was the thermal contraction responsible for the out diameter reduction. After that, the martensitic transformation takes over and the diameter contraction rate becomes lower until the out diameter begins to increase until to reach the maximum value of growth. When the volumetric fraction of martensite reaches about 70%, the thermal contraction is responsible again for the out diameter behavior.

CONCLUSION

A methodology using numerical simulations and industrial data was developed to predict the outside diameter distortion during water quenching of seamless pipes in tank.
The results of this study are summarized as follows:

- The simulation of pipe outside diameter distortion using Deform2D-HT led to a value very similar to the one measured in the industrial heat treatment line. The difference between those values was 0.02%;
- In the most of immersion time, the cooling rates at the leading end pipe were higher than at the tailing end. The possible causes could be the proximity from the internal jet;
- During the quenching process, the pipe outside diameter grows only when the volumetric fraction of martensite reaches 40% along the wall thickness;

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