Distortion in Heat Treated Tube: A Materials Engineering Approach

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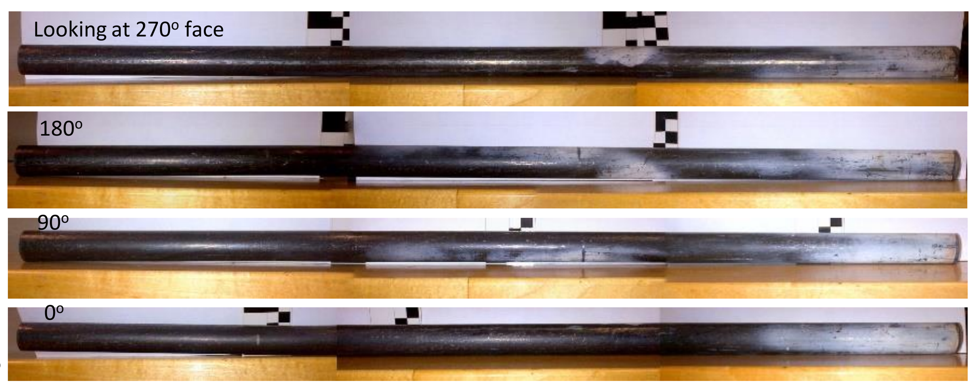
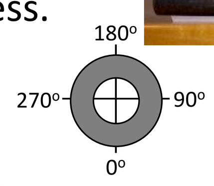
Objectives

Problem

A tube heat treater was making heavily distorted tubes with "hooked" ends on their induction heat treating line. The first and last meter of every tube was more than 1cm out of straightness.





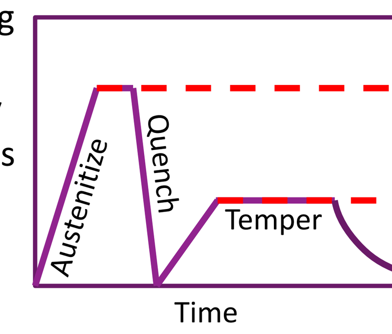
Hypothesis

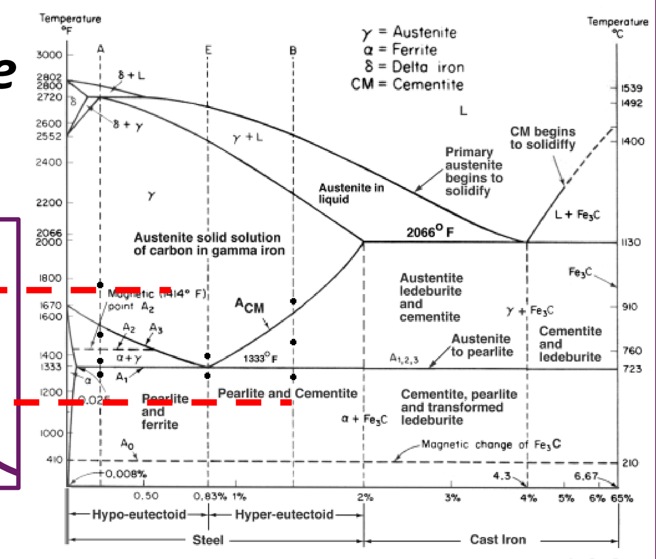
Non-uniform phase transformation can occur from asymmetric heating and cooling, and the observed distortion is due to asymmetric heating and cooling during heat treatment of the tube.

Background

Induction Heat Treating for Tube and Pipe

In-line induction heat treating of tube and pipe involves a high temperature stage (austenitizing), followed by rapid cooling (quench), and lower temperature heating (tempering). Careful positioning of the tubes within the induction coil and spray quench as well as rotation of the tubes as they are heat treated helps to ensure uniform forces and temperatures in the tubes.





Ref. [1]

Causes of Distortion in Tubular Products

Uneven heating / cooling	Residual Stresses	Non-uniform grainsize	Intricate part design
Phase change	Applied macro-stresses	Microsegregation of alloys	Poor process design

Methods

Theoretical

Calculation of volume changes due to phase transformation based on published materials data.

ρ_γ	density of austenite (kg/m^3)
T	temperature (ºC)
C_m	wt% C
ρ_α	density of ferrite (kg/m^3)
ρ_{Fe3C}	density of cementite (kg/m^3)
ρ_M	density of martensite at room temperature (kg/m^3)
α_M	linear CTE, martensite (ºC^{-1})
C_α	at% C

Ref. [2-6]

$$\rho_\gamma(T, C_m) = (8099.79 - 0.506T) * (1 - 1.46 \times 10^{-2} C_m)$$

$$\rho_\alpha(T) = 7875.96 - 0.297T - 5.62 \times 10^{-5} T^2$$

$$\rho_{Fe_3C}(T) = 7686.45 - 6.63 \times 10^{-2} T - 3.12 \times 10^{-4} T^2$$

$$\frac{1}{\rho_{\alpha+Fe_3C}(T)} = \frac{1 - \frac{C_m}{6.689427}}{\rho_\alpha} + \frac{C_m}{6.689427 * \rho_{Fe_3C}(T)}$$

$$\rho_M(C_m) = 7870.98 - 168.2C + 7.92C_m^2 \qquad \alpha_M = (14.9 - 1.9 * C_a) \times 10^{-6}$$

Simulation

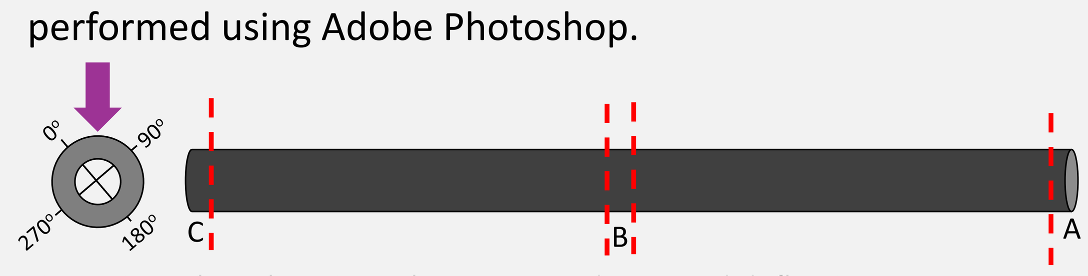
SolidWorks Simulation Express to model non-uniform volume expansion in the rotating tube.

A tube was modeled as two helices to represent the rotation of the tube on a heat treat line. The helix angle was changed to represent different rotation-to-linear motion ratios. A uniform volumetric expansion was applied to one of the two helices to determine the distortion in a tube as a function of rotation angle. One end was constrained (representing its attachment to a longer length of tube) while the other was allowed to deform freely.

Materials Analysis

Metallurgical evaluation of distorted tube.

The distorted tube was sectioned using a Leco wet abrasive saw as indicated (dotted lines). Sample orientations were carefully marked before polishing to 1 μm finish and etching with 2% Nital solution for 20 sec to enable the examination of the microstructure. Quantitative image analysis was performed using Adobe Photoshop.



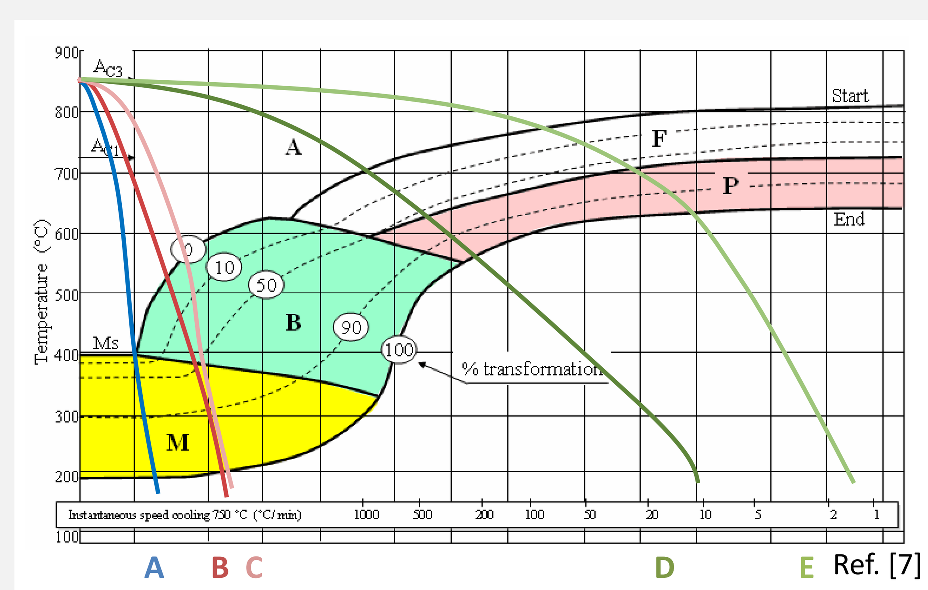
Orientation where location C has greatest downward deflection.

Results

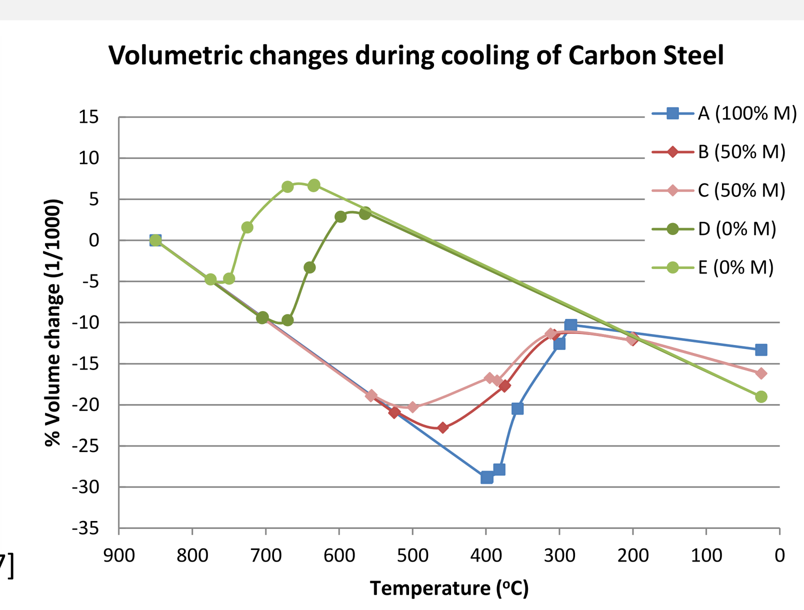
Theoretical

By plotting multiple cooling paths on a continuous cooling transformation (CCT) diagram, and calculating the percent volume change based on the phases formed, it is possible to determine the relative volume for a fully martensitic steel (blue), 50% martensite and 50% ferrite + pearlite steel (red, pink), and fully ferritic and pearlitic steel (green). The fully martensitic steel has a slightly larger volume than the others.

Volume change due to phases present in steel



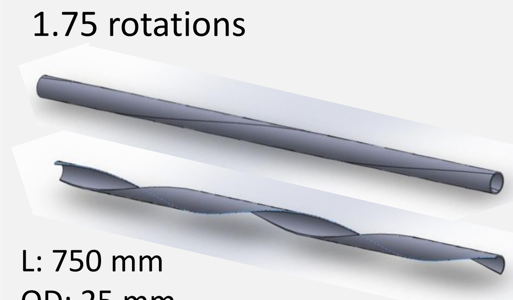
Ref. [7]



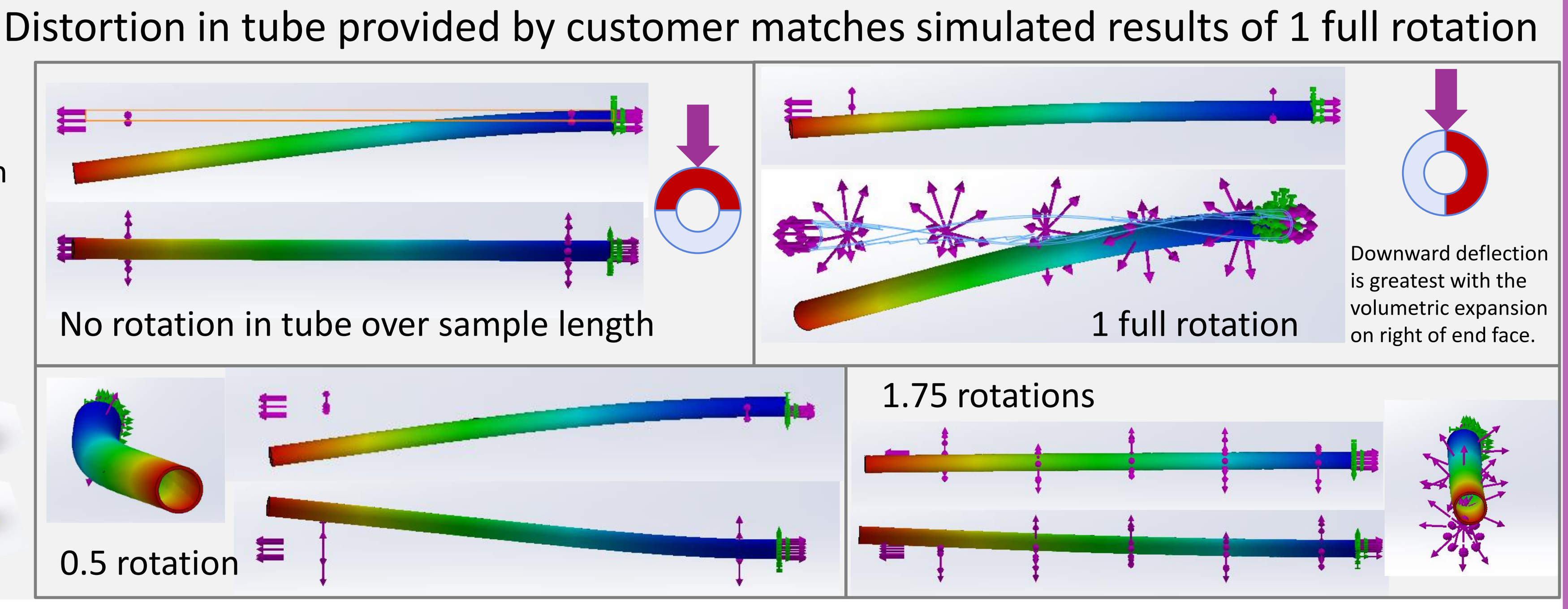
Simulation

Distortion in tube provided by customer matches simulated results of 1 full rotation

Five scenarios were modeled:
No rotation
0.5 rotation over sample length
1.0 rotation
1.5 rotations
1.75 rotations

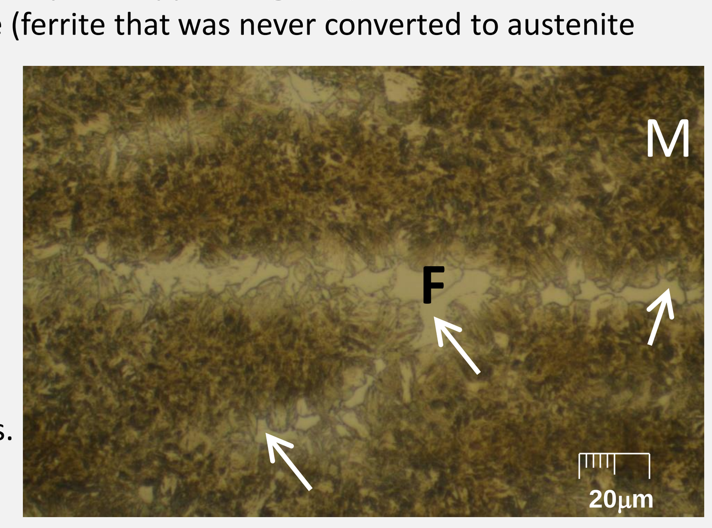


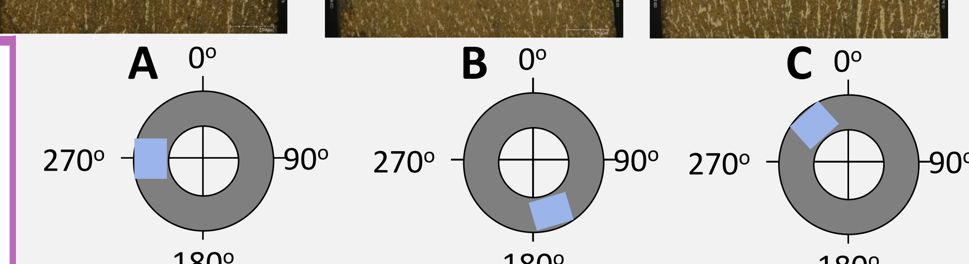
L: 750 mm
OD: 25 mm
Wall: 1.55 mm

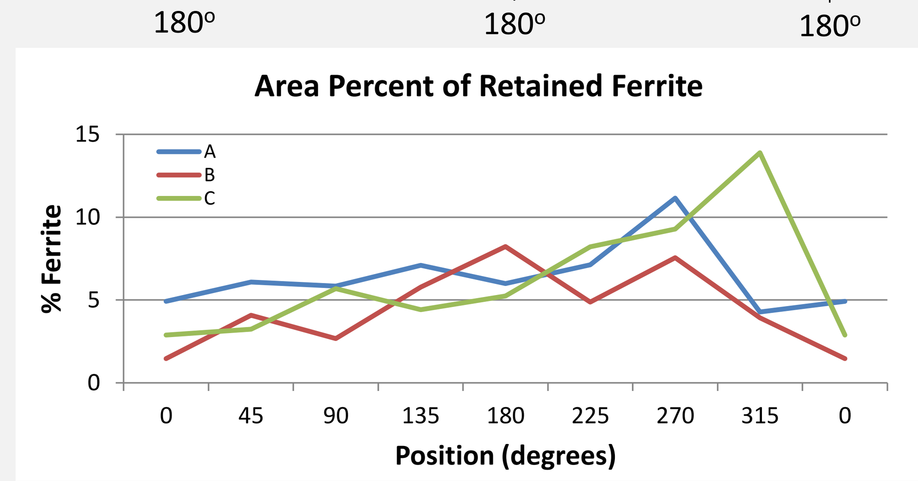


Materials Analysis

Nital preferentially attacks the carbon-rich martensite phase, making it appear dark (M). The carbon-poor ferrite phase appears light (F). In this tube there is a high amount of retained ferrite (ferrite that was never converted to austenite during austenitizing, arrows). The microstructures at several positions around the tube cross section are shown (tube surface is on the left of each micrograph). The location of the maximum amount of retained ferrite for each cross-section is shown with blue shading below the micrographs. The highest ferrite position spirals around the tube.

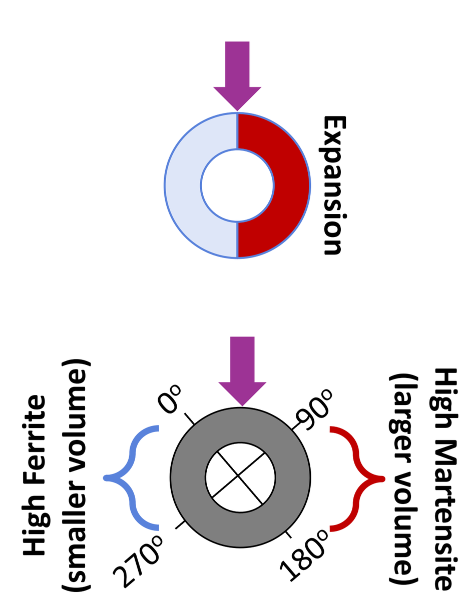






Conclusions

1. Non-uniform martensite-ferrite ratio around the tube cross-section can cause a localized volumetric expansion.
2. Localized volumetric expansion can result in distortion (hooked ends) at lower rotation-to-linear movement ratios for in-line heat treated tube.
3. A helical volumetric expansion with one full rotation over the length of the tube (75 cm) will result in a downward hook to the tube end (purple arrow) when the expanded volume is positioned at the right face of the end (red shading).
4. The tube sample provided by the customer contained significantly higher retained ferrite (smaller volume) in the 315º position of sample C, corresponding to the left face of the tube end when positioned in the greatest downward deflection orientation, thus matching the simulation results.



Recommendations to Heat Treater

1. Retained ferrite is due to inadequate heating during austenitizing. Temperature should be increased or soak time at maximum temperature should be extended.
2. Simulation results suggest that a high rate of rotation for tube may result in less deformation (even without changing heating parameters).

Ref. [8]

Acknowledgements

Thank you to Thermatool Corp., Mike DiDonato, Yoni Adonyi, and (confidential) Heat Treat Customer for providing resources and feedback for this research.

References

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