Analyzing the Effects of Quenching Methods on the Martensitic Through-Hardening of 410 Stainless Steel

PURDUE UNIVERSITY

Materials Engineering

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Less severe quenching methods were explored to test if martensitic 410-SS turbine wheels could through-harden to martensite without an oil quench. An analytical model of the cooling rates predicted that the turbine wheels would through-harden via all quenching methods tested. Lab studies showed through-hardening for all quenching methods and cooling rates. Trial manufacturing runs quenched the turbine wheels directly off the forge by either a still-air cool, forced-air cool, or box cool. The uniformity of the hardness profiles for the radial cross-sections showed that the turbine wheels tested can be through-hardened by air cooling depending on wheel size. Further studies on tempering conditions for the air quenched wheels are recommended.

CANTON DROP FORGE

This work is sponsored by Canton Drop Forge, in Canton, OH.

Project Background

410-SS contains C (0.10 - 0.15 wt%), Cr (11.5 - 13.5 wt%), Mn (max. 1.0 wt%), and Si (max 1.0 wt%).

Canton forges 410-SS wheels (5-18 cm thick) that are used in land-based turbines; they are forged via the process in Fig. 1.

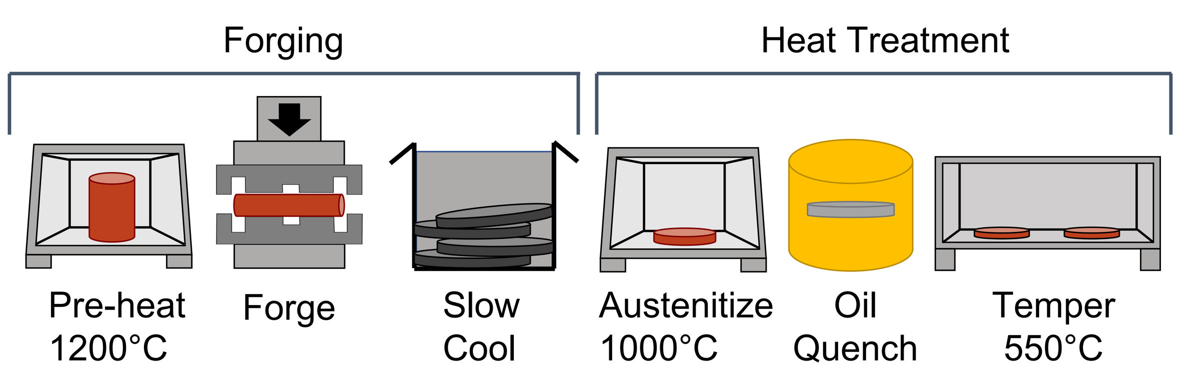

Figure 1: The established process for forging 410-SS turbine wheels consists of two stages: forging and heat treatment.

The current oil quench process guarantees the wheels through-harden to martensite, with a tempered martensite hardness within 32-38 HRC and untempered at 43 HRC.[1]

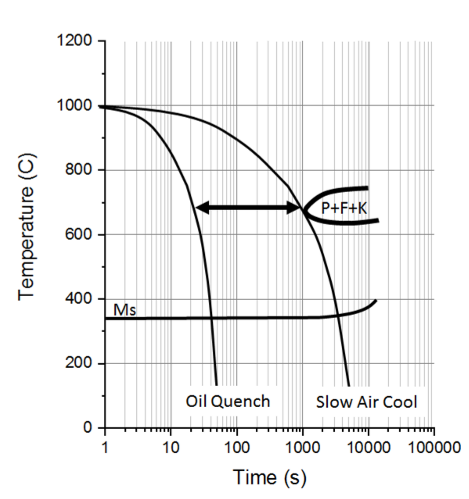

Figure 2: Qualitative cooling curves for oil quenching and the slowest possible air cool. The arrows show the range of time available.[2]

However, 410-SS has a high hardenability, so the oil quench may be unnecessary to through-harden. The continuous cooling diagram (Fig. 2) shows that cooling the entire part below ~700°C within 1000 seconds will prevent diffusional transformations and produce martensite below the Ms temperature.

Air cooling directly off the forge was evaluated via analytical heat transfer modeling coupled with lab-scale and full-scale heat treatment studies.

Technical Approach

Modeling: A lumped capacitance assumption, that includes radiation, was used with Euler's Method to find the temperature of a turbine wheel as a function of time, using the equation:

$$T(t) = \left(\frac{-1}{\rho c L_c}\right)[h(T_s - T_\infty) + \varepsilon\sigma(T_s^4 - T_\infty^4)]\Delta t + T_s$$

where variables are material properties, shape-dependent variables, or quenchant dependent.

Lab-Scale Studies: 410-SS coupons (1.8 x 1.6 x 7.1 cm) were austenitized at 1000°C/1 hr before undergoing a still-air (AC), forced-air (FC), or oil (OC) cool. They were then tempered at 565°C/2 hr. Each sample underwent hardness testing and metallography.

Full-Scale Studies: Large and small wheels underwent a FC, AC, or combined FC and box cool (FC+BC) at Canton Drop Forge (Fig. 3). Radial cross-sections of wheels were cut (Fig. 4).

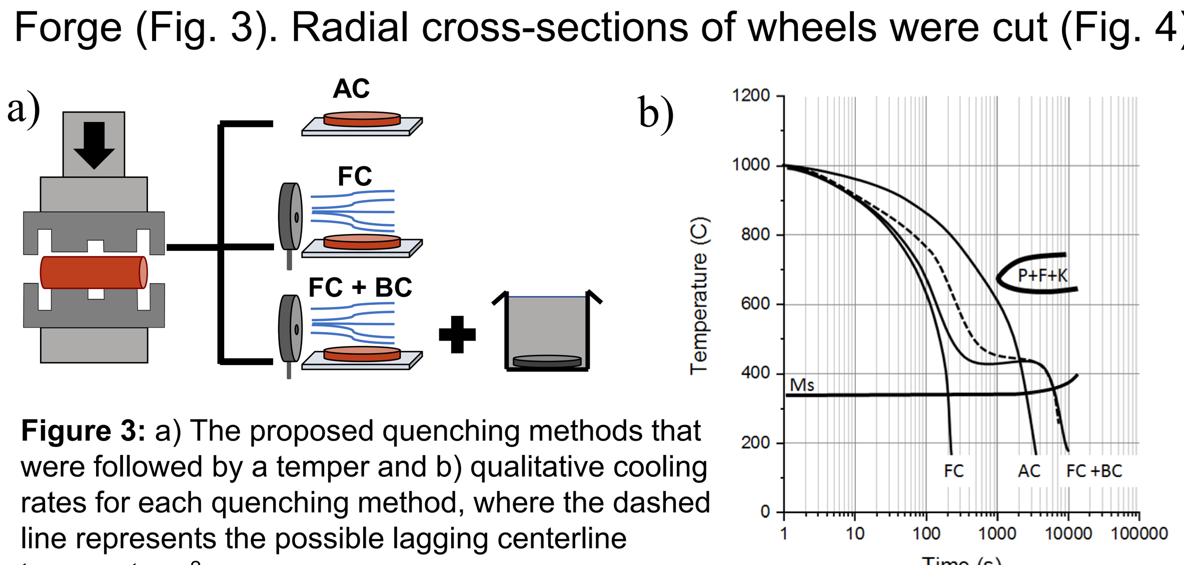

Figure 3: a) The proposed quenching methods that were followed by a temper and b) qualitative cooling rates for each quenching method, where the dashed line represents the possible lagging centerline temperature.[2]

Figure 4: a) The large and b) small turbine wheel radial cross-sections

Surface temperatures were measured with an optical pyrometer. Small wheels were left in as-quenched (Q) or quenched-and-tempered (Q + T) conditions. Hardness measurements were taken at six locations along the centerline.

Heat Transfer Modeling

Characteristic length, L_c, is the ratio of the cross-sectional area to the surface length that heat is being released from (Fig. 5). Because the wheel was cooled on a table, heat loss primarily takes place from the outer and top surface.

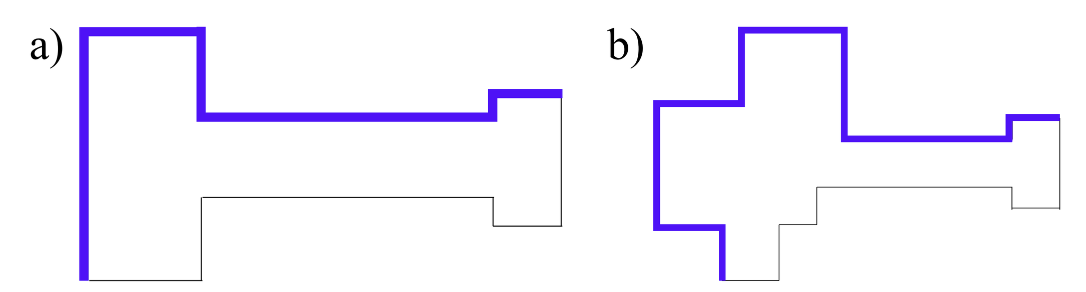

Figure 5: Blue outlines are a representation of the a) large and b) small turbine wheel surfaces that the model accounts for heat being released from.

The model, validated by the overlap seen in Fig. 6, predicts that both large and small turbine wheels will through harden to martensite via a still-air and forced-air cool.

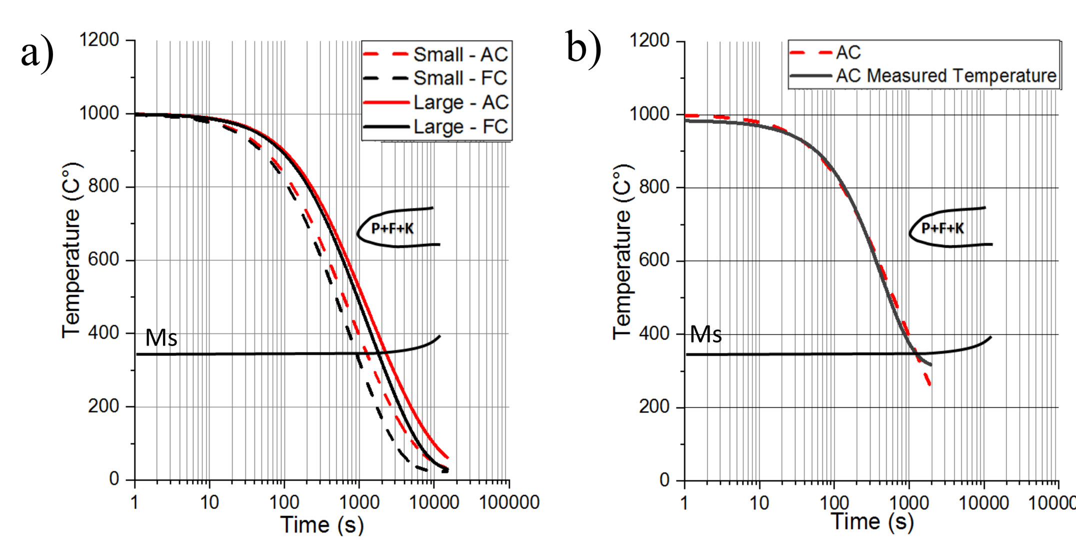

Figure 6: a) Modeled CCT diagram for the large and small turbine wheels and b) a comparison between the air-cooled small turbine wheel model and experimental surface temperatures.[2]

Lab-Scale Studies

After heat treatment the coupons had each through-hardened to martensite. After tempering, each coupon fell within the required hardness specification, as shown in Fig. 7.

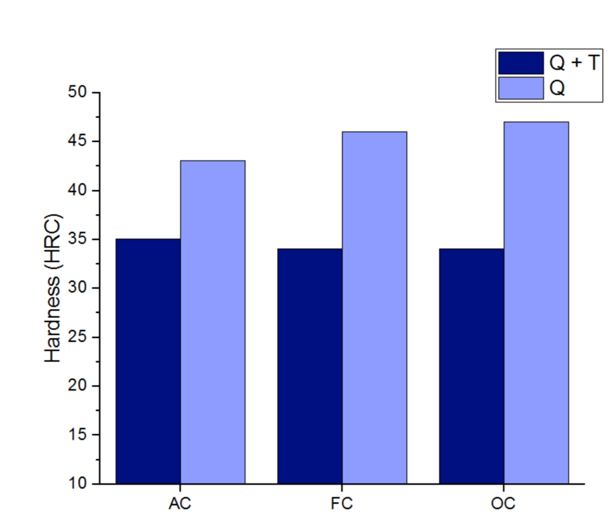

Figure 7: The hardness profiles of the heat treated coupons in both quenched-and-tempered and as-quenched conditions.

Figure 8 shows the microstructures of each of the heat treated coupons before tempering. Each coupon had martensitic microstructure throughout, ensuring each had through-hardened.

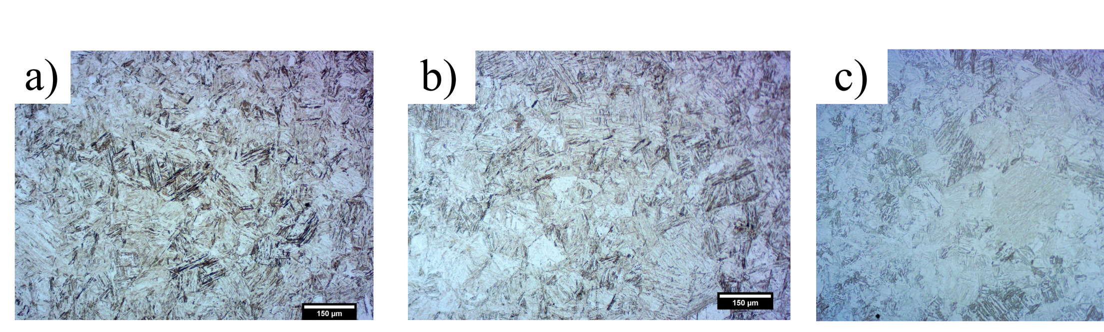

Figure 8: Cross-sectional micrographs of the a) AC coupon, b) FC coupon, and c) OC coupon

Full-Scale Studies

The as-quenched, small turbine wheels had higher hardness values than the tempered wheels (Fig. 9), but were lower than expected 43 HRC associated with martensite. However, the forced-air, as-quenched turbine wheels were close to the 43 HRC value, suggesting that they could have through-hardened, or been close to through-hardening.

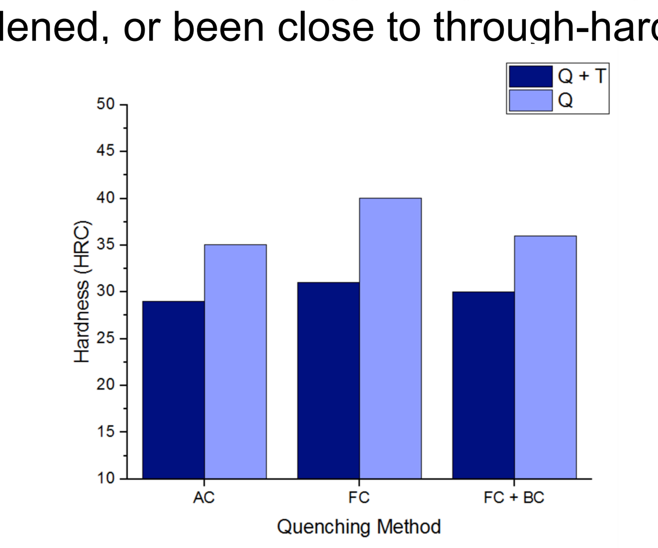

Figure 9: Comparing the average hardness values of the small turbine wheels for the as-quenched condition and the quenched-and-tempered condition.

Hardness values were analyzed with respect to position throughout the radial cross-section of the tempered turbine wheels (Fig. 10). While there is slight variation amongst individual measurements, this can be attributed to low sample size and experimental error; there is no positional dependence on hardness, meaning the turbine wheels harden uniformly.

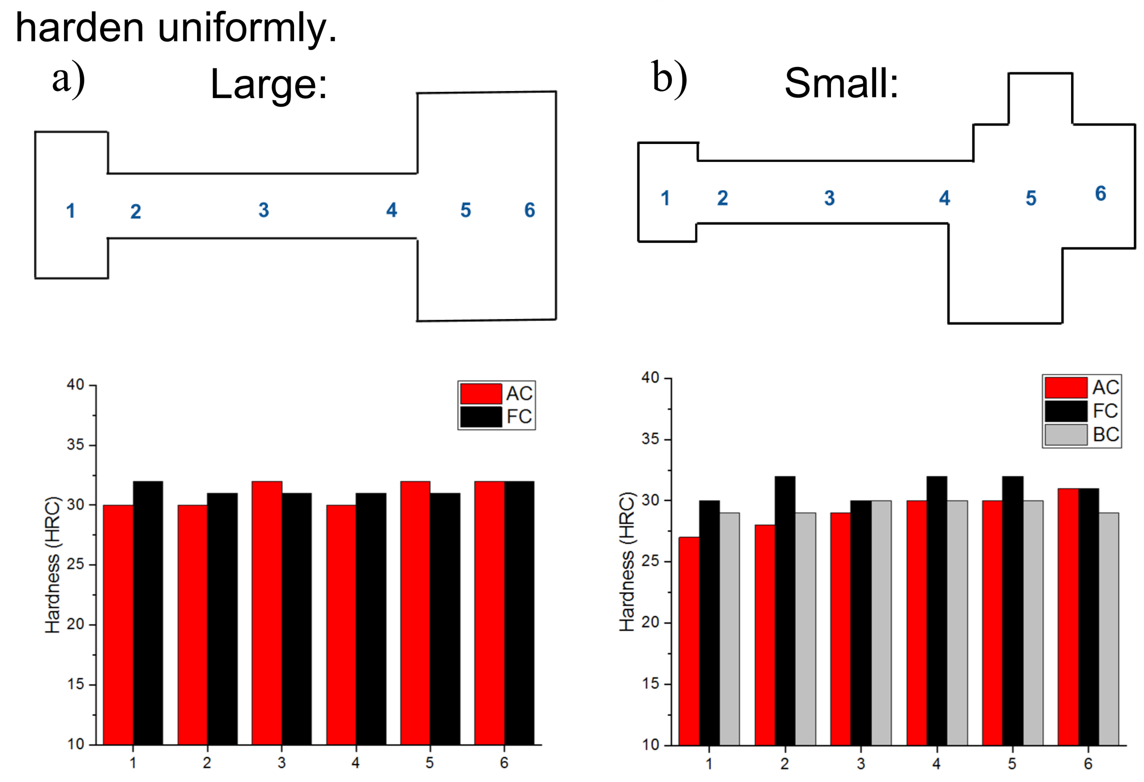

Figure 10: Radial cross-section schematic and respective hardness profiles of the tempered a) large and b) small turbine wheel.

Conclusions

1. Modeling and lab-scale studies predicted that through-hardening of turbine wheels would be possible by either a still-air or forced-air cool, dependent on turbine wheel dimensions.
2. Full-scale studies showed that large and small turbine wheels did not meet the hardness specifications after tempering.
3. While the turbine wheels may not have through-hardened, the positional uniformity and closeness of the untempered, forced-air cooled turbine wheels to the expected value suggests that through-hardening via a forced-air cool is possible.
4. It is recommended to complete further analysis on the tempering conditions in conjunction with hardness specifications.

References

[1] R.L. Rickett, W.F. White, C.S. Walton, and J.C. Butler, Trans. Am. Soc. Met., 44:138 (1952)
[2] SIJ Group. SINOXX 4006 Steel Datasheet. 2016

Acknowledgements

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