EFFECTS OF SERVICE CONDITIONS ON THE AS-MANUFACTURED RESIDUAL STRESS DISTRIBUTION IN COMMUTER CAR WHEELS

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Summary
The effects of simulated service conditions on the as-manufactured residual stress distribution in commuter car wheels are investigated. The residual stresses, those stresses which remain after all applied loads are removed, can encourage the formation and growth of fatigue cracks. The subject wheels are quenched following initial forging to increase hardness and induce residual compression in the rim. These features combine to render to the wheel more resistant to fatigue crack formation and to reduce the risk of failure in service. However, the as-manufactured net rim compressive residual stress may be reversed to tension when subjected to service loading, which includes tread braking, in railroad commuter operations. Tensile stresses at the wheel tread create an environment conducive to the formation of surface cracks that may threaten the safety of train operations.

Keywords
railroad, commuter, wheels, residual stresses, thermal cracking, stress reversal

Background

The Federal Railroad Administration of the U.S. Department of Transportation is sponsoring research to determine mechanisms causing failures in service, developing techniques for prediction of wheel failure and assessing design and operating practice options for improving wheel safety performance. The work was initiated with a simulation to predict residual stresses resulting from the heat treatment of railroad commuter car wheels during manufacture (Gordon, 1998; Gordon and Perlman, 1998). The quenching and annealing segments of the wheel manufacturing process were simulated using finite element heat transfer and stress analyses. A set of baseline parameters which characterize geometry, material properties and quench characteristics were developed which are representative of current rim-quenching practice. Results indicate the formation of a layer of residual circumferential (hoop) compression to a depth of about 4 cm (1.5 inch) from the tread surface. Variations of these parameters which account for expected ranges in North American manufacturing processes were shown to have little influence on this finding.

These results serve as the initial conditions for subsequent analysis of how service conditions may act to change the as-manufactured residual stress state. A prototype estimate of the effects of service conditions on the distribution of residual stresses in railroad commuter car wheels has been developed (Gordon, 1998; Gordon, et al 1998). Based on concepts developed at the Cracow University of Technology (Orkisz, 1990) novel software has been applied to estimate the effects of service conditions on the as-manufactured state of these wheels (Holowinski and Bobrov, 1996). Contact loads and thermal loads from on-tread braking were considered. Contact stresses alone result in increased net rim hoop compression. Thermal stresses may reverse the as-manufactured residual compressive state. In particular, high-performance stop braking can result in large hoop tension in the rim. When contact and thermal loads interact, the effects of braking dominate the process.

Tensile residual hoop stress at the wheel tread can promote the formation and growth of fatigue cracks, threatening the safety of train operations. The prototype methodology has been used to predict the depth of the tensile layer for simulated commuter operations (Gordon, et al 1998), between 0.5 and 0.6 cm (0.20 and 0.24 inch). This estimate agrees very well with the depth of the thermal cracking observed on wheels in this class of commuter service operated at 160 kph (100 mph) (Orringer and Gordon, 1996).

To extend the previous studies, a wider range of operating conditions and rail vehicle types is considered here. Pertinent variables in the current analysis include: vehicle weight, maximum operating speed and deceleration profile. This parametric analysis may permit identification those operating characteristics which are most detrimental to the safe performance of wheels in this type of service.

Analysis procedure

The procedure begins with an estimation of the heat flux due to the frictional component of the total braking force. The specific operating characteristics of a railroad must be analyzed (Gordon and Orringer, 1996). Finite element models of 81 cm (32 in) diameter, curved (or "S") plate wheels are used to compute the transient temperature and stress distributions using temperature-dependent material properties. Thermal stresses combined with initial residual stresses obtained from the wheel quenching model are used in a non-linear optimization technique which predicts the final residual stress profile. Contact stresses due to wheel/rail interaction have also been included.

A typical result is depicted in Figure 1 which illustrates the residual hoop stress as a function of depth below the wheel tread at a critical lateral location (along the line shown in the inset in Figure 1). The initial residual stresses following quenching are shown as the trace with no symbols. The results of the braking simulation with contact loads included (solid symbols) and for braking alone (open symbols) are also shown. The intersections of these curves with the zero stress abscissa indicate the depth of residual stress reversal from compression to tension. While the two curves differ in estimating the residual stress at the surface, the predicted depth of the reversed layer is 0.587 cm (0.23 in) for combined contact and braking loads and 0.553 cm (0.22 in) for braking thermal loads alone. This similarity permits estimation of stress reversal based on thermal loads alone, since contact loading complicates the analysis and vastly increases the computational time required.

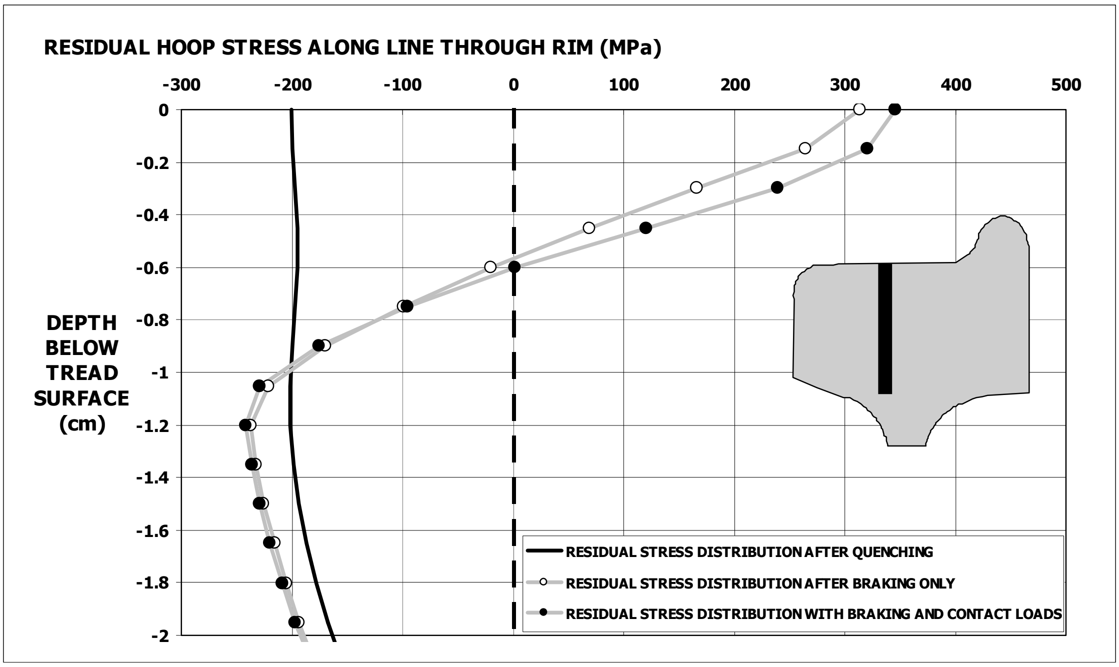

Figure 1. Distribution of circumferential residual stresses in wheel rim after simulated manufacture and service. Circles represent contact loads only; squares are contact and braking loads combined.

Effects of variations in operating conditions

To illustrate the use of the technique the operating characteristics of two New York City area commuter railroads are considered. Railroad "A" operates moderate weight vehicles in 160 kph (100 mph) service employing tread braking only. This fleet experienced widespread thermal cracking and adjusted its operations in attempts to eliminate the cracking. A different commuter fleet servicing the same geographic area is comprised of heavier equipment operating at a lower maximum speed of 128 kph (80 mph). Railroad "B" experienced very few instances of thermal cracking in its wheels. The pertinent operating parameters of the two railroads appear in Table 1.

Table 1. Operating scenarios and performance characteristics.

OPERATING SCENARIO AND BRAKING SYSTEM			VEHICLE WEIGHT	MAXIMUM SPEED	NOMINAL DECEL-ERATION RATE	MAXIMUM INSTAN-TANEOUS BRAKE POWER	MAXIMUM SURFACE TEMP-ERATURE
	Friction	Dynamic	kN (kip)	kph (mph)	kph/sec (mph/sec)	MW (hp)	°C (°F)
A-1	•		623 (140)	160 (100)	3.136 (1.96)	0.239 (320)	473 (883)
A-2	•	•	623 (140)	128 (80)	3.200 (2.00)	0.217 (291)	356 (673)
A-3a	•	•	623 (140)	160 (100)	3.568 (2.23)	0.330 (443)	348 (658)
A-3b	•	•	623 (140)	160 (100)	3.568 (2.23)	0.273 (366)	427 (801)
A-4a	•	•	623 (140)	160 (100)	3.504 (2.19)	0.298 (400)	256 (493)
A-4b	•	•	623 (140)	160 (100)	3.504 (2.19)	0.219 (294)	376 (709)
B-1	•	•	729 (164)	128 (80)	4.960 (3.10)	0.158 (212)	138 (280)
B-2	•	•	729 (164)	144 (90)	6.320 (3.95)	0.468 (628)	323 (613)
B-3	•	•	729 (164)	160 (100)	7.744 (4.84)	0.942 (1263)	575 (1067)

The results in Figure 1 describe the conditions for Railroad A when the cracking was first observed. This scenario is designated as A-1 in Table 1. A temporary restriction on the maximum operating speed to 128 kph (80 mph), designated as scenario A-2, dramatically reduced the number of occurrences of thermal cracking. The analysis was conducted with the thermal input adjusted for the reduced train speed. The results indicate that the depth of residual stress reversal is 0.16 cm (0.06 in).

To resume operation at 160 kph (100 mph) the railroad embarked on a campaign to retrofit its equipment with dynamic brakes. The vehicles in the fleet consist of married pairs (two cars semi-permanently coupled together). Of the eight axles in a married pair, six are equipped with traction motors (scenario A-3a). Following the retrofit, only the two unpowered axles had the original friction brake system (scenario A3-b). Due to additional braking capability afforded by the dynamic brakes, the braking effort required of the unpowered axles was reduced. The stress reversal analysis was repeated using the revised thermal input corresponding to the dynamic brake retrofit. The depth of stress reversal for these two cases is 0.13 and 0.40 cm (0.051 and 0.16 in) respectively, representing a significant reduction for wheels on the powered axles and a more modest decrease for the unpowered axles.

To further improve braking performance, modifications were made to provide a 26% increase in dynamic braking capability. The frictional braking effort (and thus the thermal input) was reduced again for the powered (scenario A-4a) and unpowered (scenario A-4b) axles. The results indicate no stress reversal for the powered axles with dynamic braking (scenario A-4a) and a further reduction in the predicted depth of reversal for the unpowered axles to 0.23 cm (0.09 in).

The operating parameters in scenario B-1, with all other models features unchanged, represent the baseline operating conditions for Railroad B (which has always been equipped with dynamic brakes) under which thermal cracking was only occasionally observed. The results indicate no rim stress reversal due to the applied thermal loads from braking from (128 kph) 80 mph.

The next stage of the analysis considers the outcome when changes to the operating conditions of Railroad B are adopted. It is assumed that this railroad wishes to improve service by increasing its maximum speed from 128 kph (80 mph) to 144 kph (90 mph). It is further assumed that the dynamic brake system is functioning at capacity under nominal conditions and no additional dynamic braking capability is available. The additional retarding force required to maintain required stopping distance (which is fixed by the signal spacing) from the higher speed must be provided by the friction (tread) braking system.

The retarding force from friction braking is adjusted such that the stopping distance at 144 kph (90 mph) equals that at 128 kph (80 mph). The thermal input corresponding to the increased retarding force is determined and the stress reversal analysis is repeated for this hypothetical scenario, B-2. Additional operating information for this case is provided in Table 1. The analysis predictions indicate that the modest increase in operating speed results in residual stress reversal in an extremely shallow layer (0.05 cm or 0.02 in) at the wheel tread.

The analysis is repeated assuming that the railroad is considering increasing the maximum speed of service from 128 kph (80 mph) to 160 kph (100 mph). The constraint on additional dynamic braking effort remains in effect and the tread braking effort in increased to maintain stopping distances. The increased frictional heating is recomputed and the stress reversal analysis is repeated with the adjusted thermal input. The operating parameters are listed in Table 1 as operating scenario B-3. In this case, the technique predicts the formation of a stress reversed layer approximately 0.28 cm (0.11 in) thick, significantly larger than that for simulated operation at 144 kph (90 mph).

Discussion

The results of the seven operating conditions analyzed are summarized graphically in Figure 2. The bars show the energy per wheel required to stop the vehicle and the fraction of that energy dissipated in friction braking (1 ft-lb = 1.356 J). The predicted depth of tensile residual stress reversal is indicated at the top of each bar.

To evaluate the effects of changes to operating conditions Figure 3 depicts the depth of stress reversal in the wheel rim as a function of friction braking energy. The symbols represent the results of the analysis and the trace is a linear fit to the data for cases in which stress reversal was predicted. Figure 3 indicates that, for the subject wheel design, energy input from tread braking less than 2.7 MJ during normal operations should not result in wheels with thermal cracks. Higher input energy may result in rim stress reversal, the depth of which may be estimated by the data in Figure 3.

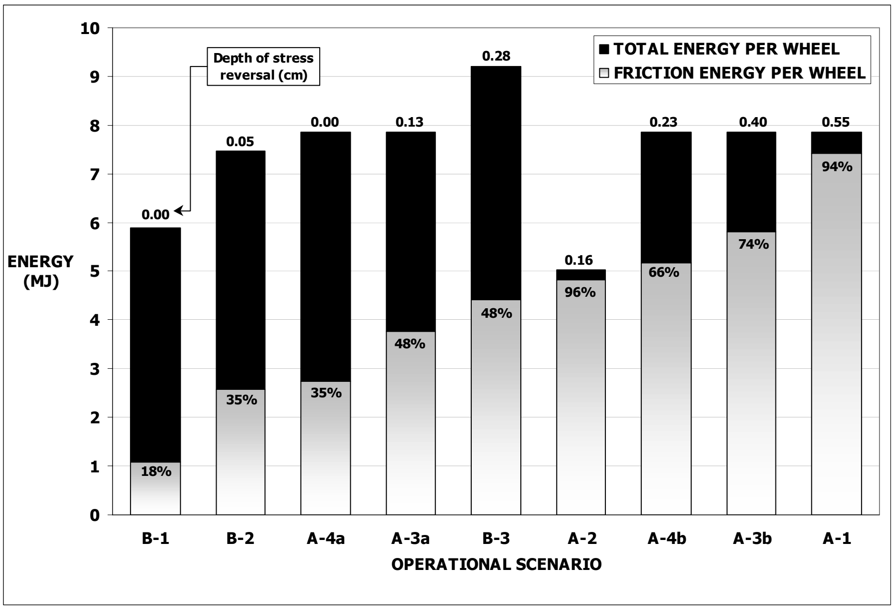

Figure 2. Summary of results of braking simulations. Bar height represents total braking energy per wheel. Shaded portion identifies frictional component. Depth of penetration of stress reversal is indicated at top of bar for each operating scenario.

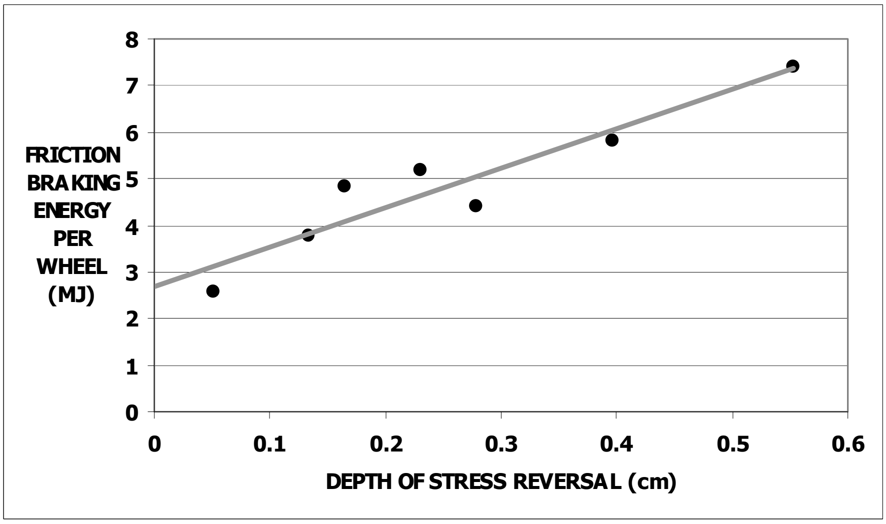

Figure 3. Analysis predictions of residual stress reversal as function of friction energy input during braking (symbols) and linear fit of the data.

While the limit suggested by these results should be deemed conservative, it is important to note that additional operational details have yet to be considered in the analysis. Wheel geometry, precise braking profiles and brake shoe effectiveness may adjust the quantitative results. Wheel wear is potentially a decisive factor which warrants further investigation. The as-manufactured compressive residual stress layer at the tread surface extends to a depth of approximately 4 cm (1 in). Deeper into the rim, a pocket of tensile residual hoop stress exists (Gordon and Perlman, 1998). As wheels wear or are re-profiled to establish proper contours, the compressive layer is gradually removed and the tread surface approaches the tensile zone. The combination of a stress-reversed layer at the surface and the residual tension in the rim presents additional risk which requires further analysis.

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