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Research Results

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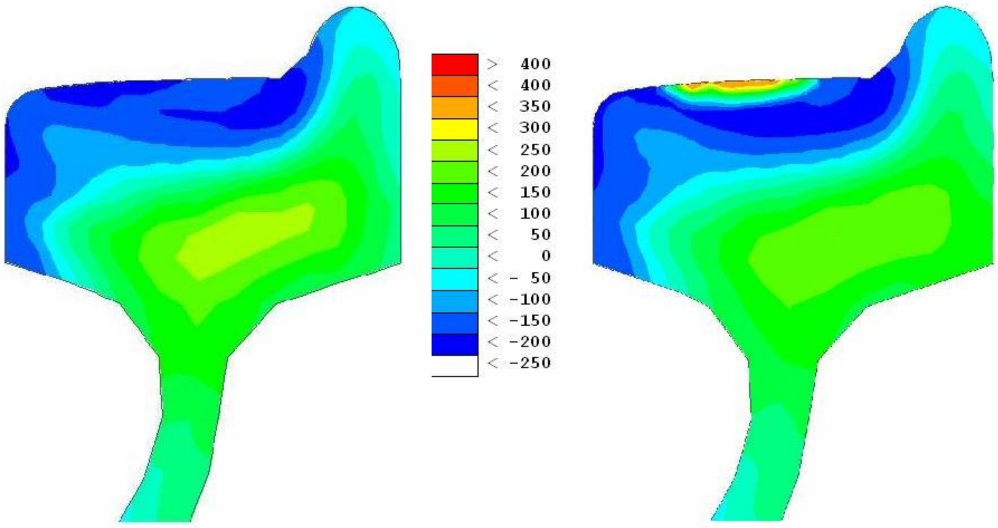
Residual Stresses in Railroad Commuter Car Wheels

SUMMARY

In the early 1990s, several railroads in the northeast experienced widespread cracking in the wheels of their commuter car fleets. Severe heating of the wheel rim during tread braking was believed to be a contributing factor. FRA initiated a research program to identify the cause(s) and establish remedial actions. This ***Research Result*** highlights some of the analysis performed in support of that effort.

Figure 1 illustrates the results of a series of calculations designed to estimate the state of residual stress in railroad commuter car wheels. Predictions of residual stresses in the wheel following manufacture are shown in Figure 1a. This is the stress state in the wheel following forming, re-austentitizing, rim-quenching and annealing. This condition is modified by contact and thermal loads when the wheel is placed in service. Figure 1b shows model predictions of the effect of the imposition of these service loads. Notice that the wheel rim is in residual compression when the wheel is new. After simulated service, the region in the center of the tread has reversed to tension. This condition can lead to the formation and growth of fatigue cracks ("thermal cracks") in the rim which can ultimately lead to premature failure of wheels in service.



(a) **(b)**

Figure 1. Estimates of residual stresses in a commuter car wheel: (a) following manufacture and (b) after simulated service. Contour levels in megapascals, MPa (6.895 MPa = 1 ksi).

BACKGROUND

In 1991, Federal Railroad Administration (FRA) inspectors became aware of a wheel thermal cracking epidemic in certain commuter car fleets [1]. Upon investigation of the damaged wheels it was determined that the cracking was caused by thermal fatigue during on-tread friction braking. The thermal cracks appear as short cracks oriented axially on the wheel tread as shown in Figure 2. Figure 3 shows the fracture surface of one of these cracks in which the characteristic benchmarks confirm fatigue as the crack growth driving mechanism. Thermal fatigue due to repeated brake applications from high speed was identified as the primary contributor to the observed cracking.

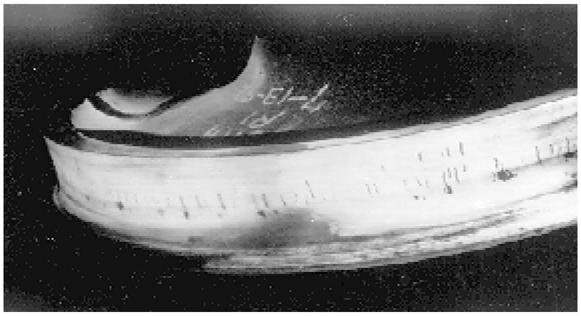


Figure 2. Thermal cracks on commuter wheel tread.

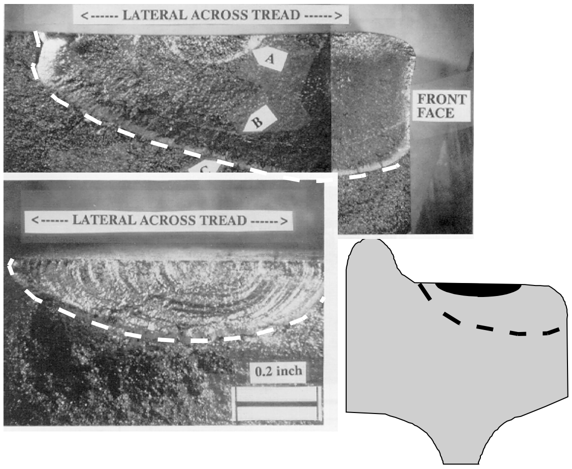


Figure 3. Fatigue crack profile.

WHEEL PERFORMANCE ANALYSIS

Following the preliminary investigation, a research program was developed to study the wheel cracking phenomenon. The focus of this program involved estimating residual stresses in wheels. Residual stresses are those which remain in a structure after all external loads are removed. These stresses have been shown to contribute to the formation and growth of fatigue cracks.

To characterize these stresses, the combined effects of manufacturing and service conditions must be included. Residual stresses are induced in the wheel during manufacture and this stress state is subsequently modified when the wheel is placed in service, due to cyclic contact loads and thermal loads imposed during on-tread friction braking.

WHEEL MANUFACTURING PROCESS

The commuter operations which experienced the thermal cracking problems used the same type of wheels, 32-inch (81 cm) reverse-dish (or S-plate) wheels. A schematic of the wheel cross-section is shown in Figure 4. The S-plate is used in applications in which high-performance stop braking is required in service. The curved plate acts like a spring and permits radial breathing of the rim when it is heated during friction braking. This action reduces the thermal stresses developed in the rim of the wheel.

The wheels are manufactured using a multi-step forging process to initially shape the wheel. Next, to remove undesired residual stresses which remain after forging, they are reheated to a temperature above the austenitizing temperature (*Af*=871°C or 1600°F in this example). Once reheated, the wheels are rim-quenched using a water spray to produce a fine-grained pearlitic microstructure and induce beneficial circumferential (hoop) residual compressive stress at the tread surface. The residual stress distribution inhibits the formation of fatigue cracks in the rim and also retards the growth of these cracks should they manage to form. Following quenching, the wheels are placed in an annealing furnace for several hours to reduce the levels of residual stress. After this heat-treatment, the wheels are exposed to ambient conditions as they cool to room temperature. The resultant distribution of residual stresses represents the as-manufactured condition of "new" wheels, and is a required component for the assessment of service conditions. A finite element simulation of this process has been conducted using ABAQUS [2]. Additional details of the analysis can be found in [3] and [4].

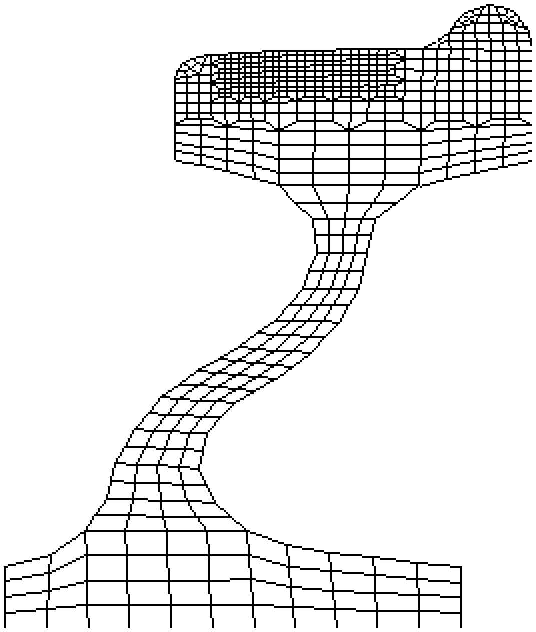


Figure 4. Commuter wheel cross-section.

The residual circumferential hoop stress in a new wheel is shown in Figure 1(a). This distribution exhibits residual compression at the tread surface which inhibits crack formation and aids in retarding growth if cracks do manage to form. This residual compression "squeezes" the crack closed, making it more difficult for it to propagate.

However, when wheels are placed in service, the combined action of contact and thermal loads from braking can alter this as-manufactured condition.

WHEEL SERVICE LOADING

Wheels in service experience repeated contact loading, and the stresses due to contact between the wheel and the running rail are determined next. The vehicle is assumed to weigh 140,000 lbs (623 kN) which implies a static wheel load of 17,500 lbs (78kN) applied to the 132 lb. rail. As this study is concerned with the stresses in the wheel rim in the vicinity of the center of the tread (where the thermal cracking is observed to occur) candidate contact locations have been selected in that region.

The braking simulation requires quantification of the thermal input to the wheel due to frictional heating to assess the effects of thermal loads on the as-manufactured residual stresses in the rim. The goal of this analysis is to obtain the elastic stresses in the rim due to the thermal gradients induced by heating during on-tread braking, and is conducted in much the same way as the manufacturing process simulation, in that the heat transfer and mechanical calculations are conducted separately.

The heat flux (energy) generated at the brake shoe is determined from data obtained from the transit authority regarding the performance characteristics of the Electrical Multiple Unit (EMU) vehicles which operate at 160 kph (100 mph) and are service braked at a rate of 0.8 to 0.9 m/s^2 (1.7 to 2 mph/s). This information is translated into effective retarding force per wheel, which is then expressed in terms of brake power. Additional details regarding the braking simulation can be found in [5].

The stresses determined for contact and braking are combined using specially-developed software which predicts the final residual stress distribution. The post-quenching stresses are used as an initial condition. Then, the contact and braking loads are applied. The result of the analysis is shown in Figure 1(b). It shows a reversal of the as-manufactured residual compression to tension in a layer just below the tread surface.

The residual tension at the tread surface, which tends to "pull" cracks open, will promote their growth through the tensile layer. Once the crack front encounters subsurface residual compression, further growth is suppressed. These preliminary results are encouraging, since the depth of the predicted stress reversal corresponds to the average depth of the cracks which were found in the wheels of this particular fleet.

CONCLUSIONS

This study has demonstrated an approach for simulating the effect of service conditions on the state of residual stresses in wheels. A parallel effort is underway to obtain estimates of residual stresses experimentally. The experimental results will be used to calibrate the model described here. This will permit application of the simulation technique to other kinds of rail operations (different vehicles, speeds, etc.) as well as extension of the study to freight wheels.

WANT MORE INFORMATION?

Additional details on the manufacturing and service loading simulations have been published in two technical papers which are available at ***http://www.fra.dot.gov***.

ACKNOWLEDGMENTS

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