MATERION

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TECHNICALTIDBITS

MATERION PERFORMANCE ALLOYS

FASTER TO DISASTER: **SPEED-RELATED SCALING EFFECTS**

Recall that the **kinetic energy** of an object in motion is half the mass times the square of the velocity. Kinetic energy is therefore a linear function of an object's mass.

However, since mass is directly proportional to volume, and volume is a cubic function of length, kinetic energy increases as the cube of an objects size, if scaled isometrically. Kinetic energy is also a function of the square of velocity. This is a prime example of a parameter that scales nonlinearly with speed. In a crash, an object will have four times as much kinetic energy to dissipate if it is travelling only twice as fast. So, in a high speed accident, doubling the speed effectively quadruples the severity. This is why speed is such an important consideration in engineering design.

Increased speed has two effects on the fatigue life of a part. The first is actually good news. For cyclically loaded components, a faster speed means that each cycle is completed more quickly, so the **strain rate** is higher. The fatigue life of most metals actually *increases* with strain rate, due to a phenomenon known as **strain rate hardening.** (There will be more on this subject in next month's edition.) However, this beneficial effect is more than offset by the fact that it will take less time to reach the point of failure, even if the total number of cycles is greater.

Perhaps the most famous disaster in which speed played a major role was in the 1998 derailment and subsequent crash of the Inter-City Express (ICE) train 884 near Eschede, Germany. (Speed also played a major role in the sinking of the Titanic, but there were plenty of other causes of that particular disaster.) The derailment ultimately occurred because the wheel design (which had been used very successfully on lower speed, lower weight light rail cars) turned out to be inappropriate for use in high speed trains.

To mitigate noise and vibration, **monolithic** (made entirely of one material) steel wheels were replaced by what are known as resilient wheels. These wheels feature a rubber dampener around the center hub with a steel rim around the outside of the rubber. The rubber is less stiff than the steel, and effectively dampens vibrations, shocks and noise. These wheels had proven track records on street cars and light rail systems, and were very effective at reducing noise and creating a smoother ride. These wheels are still used today (quite effectively and appropriately) in such systems. However, such wheels had never before been used on a high speed intercity train.

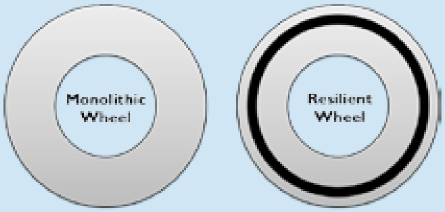

Figure 1. Crude Schematic of Wheel Designs.
The original (monolithic) wheel was entirely made of steel. The replacement (resilient) design included a rubber dampener between the center hub and outer rim to absorb vibration and allow for a smoother, more quiet ride.

I feel the need – the need for speed!
How changes in speed affect the way that materials and environmental forces interact.

- **Kinetic Energy**
- **Strain Rate**
- **Strain Rate Hardening**
- **Monolithic**

The next issue of Technical Tidbits will discuss the effects of strain rate hardening

FASTER TO DISASTER: **SPEED-RELATED SCALING EFFECTS** (CONTINUED)

In this particular disaster, there was a fatigue crack on the inside of the rim of a wheel on the first car, where it went undetected during periodic inspection. The crack progressed outward, until the rim fractured and peeled away, kicking off a cascading sequence of small failures that progressed to disaster. To make a long story short, the broken steel rim on the wheel embedded itself in the car bottom and caused the wheel to derail. The derailed wheel struck and activated a turnout switch, which caused the third and subsequent trailing cars to switch to an adjacent track and derail. Since the accident happened to occur under an overpass, the derailed cars struck and destroyed the bridge supports, causing the bridge to fall down, crushing some of the trailing cars underneath, while the remainder of the cars piled up against the fallen bridge at 200 km/hr. 101 people lost their lives, including railway employees who happened to be working along the tracks. 88 additional people were injured.

In the monolithic wheel, the highest tensile stress occurs on the outside diameter and that is where fatigue cracks would originate. These cracks would be easily visible to the wheel inspectors. In the resilient wheel, the fatigue cracks could potentially originate on the inside of the steel rim and would most likely not be visible upon inspection until they had progressed to the point of catastrophic failure. This is precisely what happened on the ICE 884. See Figure 2 for a crude model of the peak tensile stress distributions in these wheels (2D slices, with geometry greatly simplified).

Figure 2. Tensile stress distributions the different wheel types, before and after wear. The monolithic wheels show peak tensile stress on the outer rim. The resilient wheels show much higher peak tensile stresses of on the inside diameter of the outer rims. The stresses are higher in the worn wheel than in the new wheels. (The numbers are not shown because this is a qualitative, not a quantitative analysis, due to the many simplifications and approximations.)

From my point of view, there were four factors in the use of this wheel on the high speed train that contributed to its failure in this particular application. (We will focus on the wheel exclusively here, and ignore the other factors that contributed to the disaster, as they are well documented elsewhere.)

1. Higher speed, resulting in a higher strain rate. Even though the effective yield strength, tensile strength, ductility and fatigue life (number of cycles to failure) would most likely have been slightly increased, the number of cycles per second was much higher, resulting in a shorter time to failure.
2. Higher load, leading to greater strain. A larger, heavier train meant that there was a greater amount of flexure of the wheel rim. So the initial strain at peak load on the wheel during each cycle was higher so the initial strain and stress amplitudes were higher.
3. Faster wear, resulting in increasing strain amplitude over time. As the wheel rim wore more quickly, it became thinner and less stiff, resulting in even greater flexure, stress and strain with each cycle.
4. Fatigue crack initiation and growth in a spot that could not be detected in visual inspections.

The most important takeaway is that even if design is proven to work at low speed, it may not work at high speed without extensive modifications. Higher speeds can greatly accelerate the failure process, at a rate disproportionate to the increase in speed.

Written by Mike Gedeon of Materion Performance Alloys Marketing Department. Mr. Gedeon's primary focus is on electronic strip for the automotive, telecom, and computer markets with emphasis on application development.

References:

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Materion Performance Alloys
6070 Parkland Blvd.
Mayfield Heights, OH 44124

MATERION

Sales
+1.216.383.6800
800.321.2076
BrushAlloys@Materion.com

Technical Service
+1.216.692.3108
800.375.4205
BrushAlloys-Info@Materion.com