Detecting residual stress in rails

Unequal cooling introduces residual stresses in rail that have the effect of shortening its useful life. Barkhausen Noise Analysis techniques could make it relatively simple to detect high stresses locked into a rail

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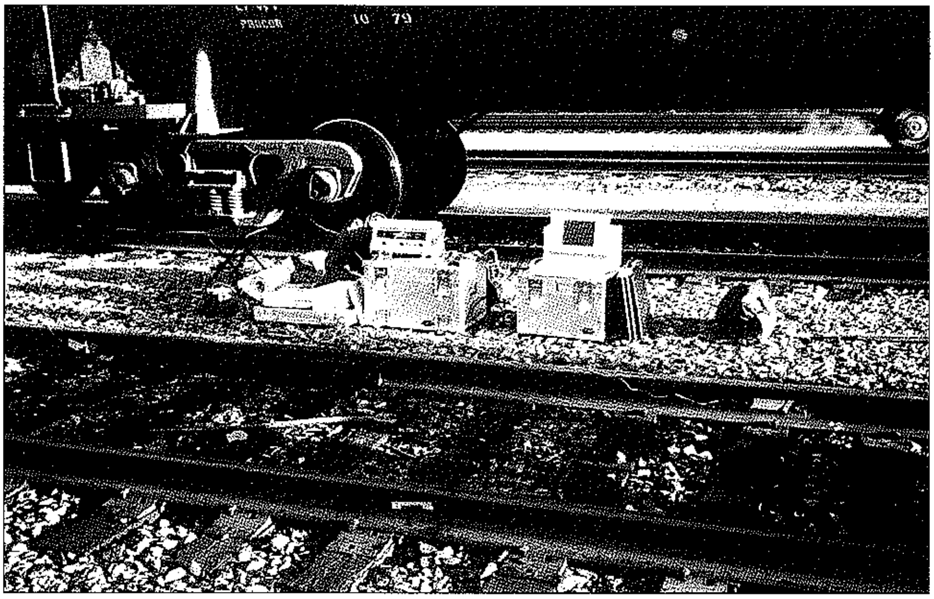
RESIDUAL STRESS has been described as a 'silent killer' of materials which 'can lead to failure at external loads far below those predicted based on strength.' This is because 'the real load seen by the material is a combination of the applied load and the internal stresses caused by this phenomenon.'[1]

This warning from J S Heyman, Head of the Nondestructive Measurement Science Branch and Manager of the Nondestructive Evaluation Research Program at NASA in 1989 merits its attention by anyone involved with rail. Typically, rail contains complex patterns of residual stress locked in during manufacture. When these are added to stresses generated by static and dynamic wheel loads, the steel can experience much higher stresses than calculations based solely on the prediction or measurement of external forces would suggest.

A major difficulty lies in the detection by nondestructive methods of residual stresses in rail. If they could be at least qualitatively identified, there is potential for identifying those parts of rail that have the potential for causing problems. To solve this problem, I have been researching the use of Barkhausen Noise Analysis techniques, with support from the National Research Council of Canada[2].

BNA measures surface stress, not internal stress. With the exception of internal flaws, and certain other extraordinary circumstances, cracks develop from the surface, so BNA can be used to seek out areas of high stress that contribute to rail problems. To measure surface stress, BNA uses variations in magnetic response when reversing electromagnetic fields (similar to those used in magnetic particle crack detection) are applied to the rail. An active response indicates high stresses.

Using BNA instrumentation which is commercially available from American Stress Technologies, and a sensor developed during the research, two types of rail have been investigated and others briefly examined. Fig 1 presents results from laboratory and field work.



A BNA field test was conducted at BC Rail's North Vancouver Yard using an hydraulic rail puller; the main instrumentation is central, with a strain gauge laptop (left) and portable computer (right)

By taking measurements at specific angles and combining these, a stress correlation with the magnetic response is found using the BNA results. As the BNA instrument is transportable and can be battery powered, it is relatively simple to search along the length of rails for high vertical web stresses, for example. When associated with stress risers such as a joint, such stresses are liable to cause problems.

This procedure could ideally be used during manufacture of the rail. By identifying high stress areas, the acceptability of the rail could be determined without destroying it. By checking the rail continuously, BNA could supplement web saw cutting which is presently used for residual stress quality control. By testing around the joints, areas of high tensile stress could be treated by peening to produce residual compressive stresses which would be much less likely to develop fatigue cracks.

Of perhaps the greatest practical value, field and laboratory tests have shown that BNA techniques can be used non-destructively to determine the neutral temperature of rail in the track.

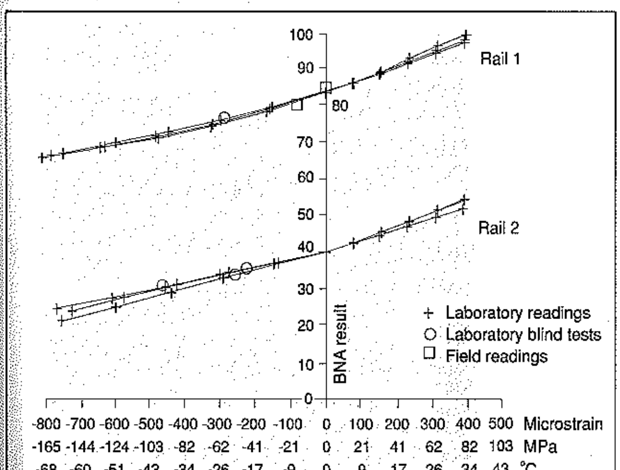


Fig 1. Correlation between rail stresses and Barkhausen Noise Analysis for laboratory and field tests

ORIGIN OF RESIDUAL STRESSES

Rail has a bulbous head, a slender web and a substantial tapered foot. During cooling after the rail is shaped by rolls, heat loss from any point is determined by the shortest distance to the coolest outer surface. Hence heat loss is fastest in the web and the edge of the foot which protrudes up from the cooling bed (out of contact with the adjacent rail's hot head), and slowest in the head. This differential cooling generates residual stresses.

When the rail is being shaped by the rolls, it is white hot so relatively little stress causes plastic strain to occur; the E value is reduced. As the rail cools, the outer skin increases in strength as it cools and contracts, compressing the still soft inner steel and plastically deforming it. In the process, the outer steel is placed in tension and residual stresses are generated.

As cooling proceeds, there is a variation in E value between head, web and foot because the slender web cools more quickly. Variations in

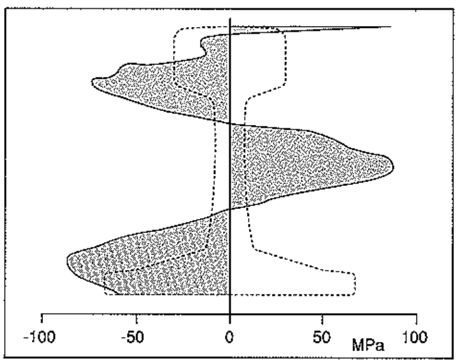


Fig 2. Longitudinal rail stresses found after cooling (Fischer et al)

stress and strain follow, and the result is a very complex arrangement of residual stresses.

Various theoretical and empirical studies have been undertaken to identify these stresses, and Fig 2 shows a typical result.[3] While this phenomenon occurs in any rolled steel beam, these are normally of a more uniform section than rails. Permanent way engineers need to be aware of the implications for residual stresses.

Head hardening

When rail is head-hardened, the steel in the head is transformed into a material having a denser structure. Because the head shrinks relative to the web and foot, the rail emerges from the head-hardening station in a sagged shape.

The rail is therefore passed through rollers to stretch the head plastically and compress the foot, and thus straighten it in the vertical plane. Typically, the consequence is a very high longitudinal stress in the head, a compressive stress in the web, and tensile stress in the foot (Fig 3)[4].

Whether or not it is head-hardened, rail is normally subject to roller straightening in both vertical and lateral planes. Consequently, most rail contains residual stresses that are generated in two inter-related ways.

As already noted, the steel is plastically deformed to yield it into the desired straight shape. In addition, the roller contact strips on the rail surface – typically the top of the head, the base of the foot, and the lower part of the web beneath the brand marks – are subject to yield-level contact stresses from the rollers.

Controlling residual stresses

The straighter the rail as rolled and the more controlled the cooling, the less the residual stresses will be. While rail manufacturers have expended much effort to optimise both, most rail still has quite complex arrangements of residual stresses which vary along its length.

Consider the rail as it passes through the roller straightener. The lead and tail ends are relatively free to deflect under the force of the rolls, whereas for most of the rail length the section within the rolls is constrained by the rail on each side.

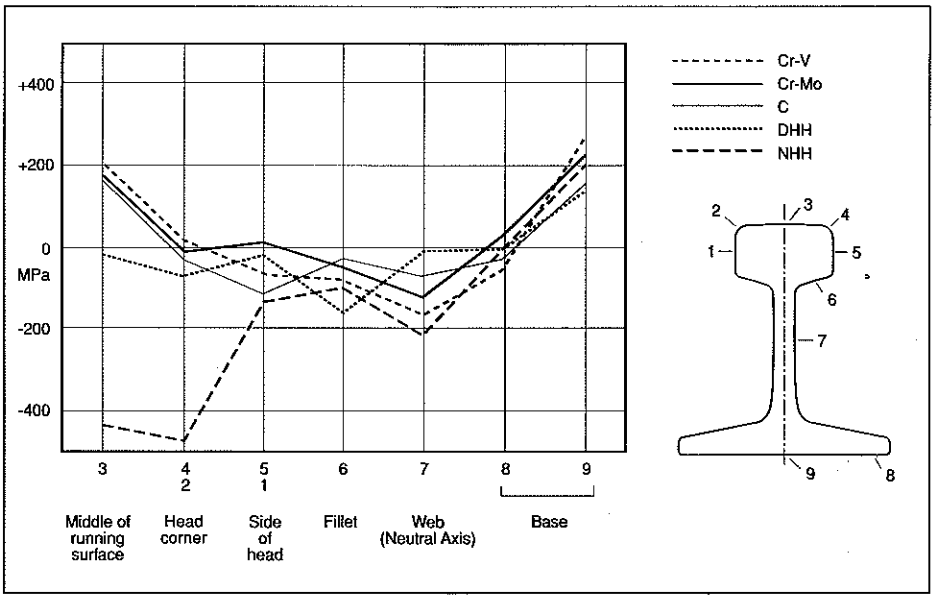
Any quality control process aimed at detecting residual stresses must recognise the variations at rail ends inherent in roller straightening. For example, if a rail is cut to form a closure, the residual stresses present at the cut end will be different to those at the original end; any longitudinal stresses become vertical stresses at a cut end.

The stress picture is further complicated by the fact that the amount of straightening force required will vary as between rails, and indeed between different parts of the same rail. Residual stresses will vary accordingly. Manufacturers strive to minimise the need for roller straightening, cool the rail as evenly as possible, and harden it in such a way as to minimise the need for subsequent straightening – by hardening the foot as well as the head, for instance.

Measuring residual stresses

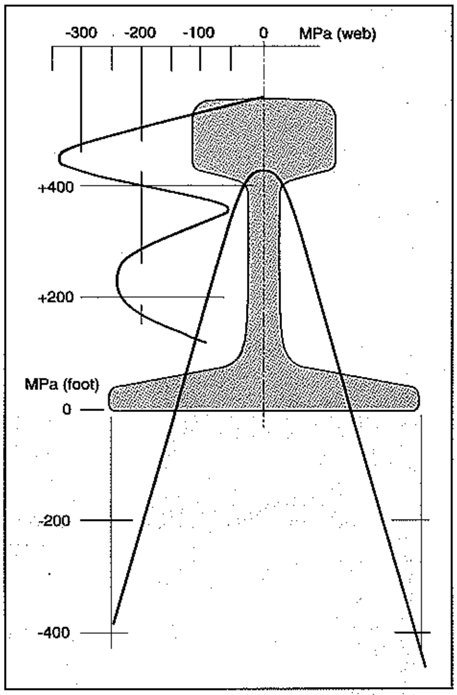
Given that residual stresses can reach near-yield both in compression and tension, and their variability both within the cross-section and along the rail, it is hardly surprising that it is difficult to obtain credible stress readings. An enormous amount of strain gauge slicing work was done by Russian researchers to identify optimal head hardening and roller straightening procedures some 25 years ago.[5] An example is given in Fig 4.

Since then, others have used a variety of techniques. Neutron diffraction, for example,



Above: Fig 3. Typical longitudinal residual stresses after rail straightening (Urashima & Sugino)

Below: Fig 4. Residual strain variations in web and foot of rail, found by strain gauge slicing (Konyukhov et al)



Détection des contraintes rémanentes dans les rails

Le refroidissement irrégulier et le dressage des rails aux rouleaux pendant la fabrication introduisent des contraintes résiduelles qui peuvent être importantes. Lorsque celles-ci viennent s'ajouter aux contraintes normales causées par la charge dynamique des roues, toutes ces contraintes ensemble peuvent réduire significativement la résistance prévue à la fatigue avant l'apparition de fissures et autres défauts. Les contraintes résiduelles sont difficiles à mesurer mais avec les techniques d'analyse de bruit Barkhausen, détecter des contraintes bloquées dans un rail pourrait être relativement aisée même une fois le rail mis en place

Ermittlung von Eigenspannung in Schienen

Ungleichmäßige Abkühlung und Walzrichten von Schienen während der Herstellung können erhebliche Eigenspannungen einbringen. Zusammen mit den normalen, durch dynamische Belastungen seitens der Räder verursachte Spannungen können diese die voraussichtliche Dauerhaltbarkeit bis zur Entstehung von Rissen und anderen Defekten erheblich reduzieren. Eine Messung der Eigenspannung ist bekanntlich schwierig - die Geräuschanalysentechnik von Barkhausen könnte die Ermittlung von in Schienen befindlichen Spannungen relativ vereinfachen, auch wenn diese in der Gleisanlage installiert sind

La detección de esfuerzos residuales en los rieles

La desigualdad en el enfriamiento y enderezamiento por laminador en la fabricación de rieles introducen esfuerzos residuales que pueden alcanzar considerable magnitud. Si se añaden estos a los esfuerzos normales causados por la carga dinámica de las ruedas, el efecto puede redundar en la reducción substancial de la vida prevista basada en la fatiga antes de que aparezcan y se desarrollen grietas y otros defectos. El esfuerzo residual es muy difícil de medir, pero las técnicas de análisis de ruido Barkhausen podrían facilitar enormemente la detección de esfuerzos bloqueados en un riel aun cuando ya esté instalado en la vía can probe deeply into steel[6] with typical results shown in Fig 5. However, all this work is constrained by the variability of the stresses. While useful, these laboratory methods are expensive and each has technical limitations. Moreover, the rail has to be cut up, and since the stresses vary so much from one rail to another, this limits the utility of the results.

Much further work has also been conducted using a mixture of techniques to obtain stress measurements so that the limitations of one are offset by another[7], but it is still necessary to infer from tests on one destroyed rail what the stresses in rails produced by the same process will be. The goal is to measure stresses non-destructively during manufacture, and when rail is in the track.

To take but one example, in-situ measurement of rail stresses can be used to calculate the neutral temperature of a given rail. But where exactly and how to take this measurement with confidence, preferably from a moving vehicle, remains a challenge. Residual stress differences between head, web and foot could be as much as 10 times larger that the 20MPa mean stress difference across the whole cross-section induced by an 8°C change in ambient temperature.

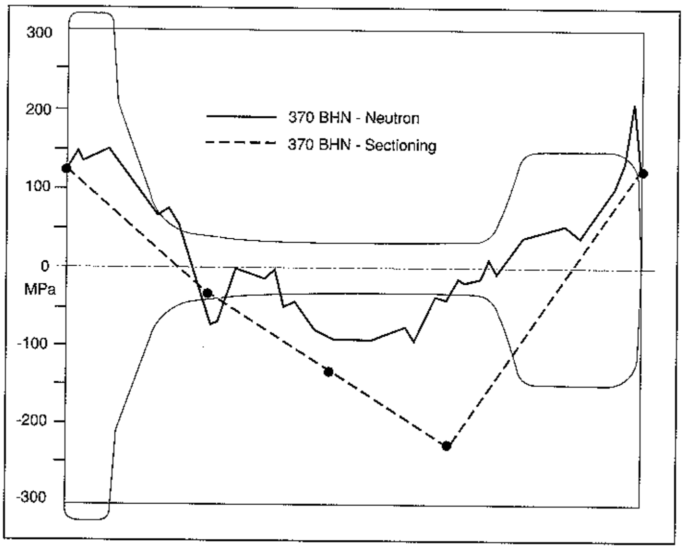


Fig 5. Longitudinal residual stresses on rail axis as determined by neutron diffraction (Webster et al)

Implications

High stresses seek to relieve themselves. The whole process of rail management from rolling mill to track needs to be undertaken with stress consequences in mind.

The development of a practical means of measuring rail stresses in track is potentially of great importance. Track stability, rail fatigue resistance and joint verification could all be improved with better stress measurement tools. The BNA technique described here could contribute to track management by identifying when and where high stresses locked into rail need attention. □

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