Nondestructive Testing of Railroad Rail

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Techniques of nondestructive testing (NDT) of railroad rail in service are reviewed with the aim of assessing the state of the art and future needs. The contributions to the industry of the primary NDT methods—ultrasonic and magnetic inspection—are noted, and their limitations are examined. The limitations of ultrasonic inspection include ensuring the coupling of the ultrasonic signal into and out of the rail, setting the sensitivity level of the inspection system reproducibly, and relating the amplitude of the return ultrasonic signal to the size of the defect. Magnetic inspection is generally limited to the railhead. The two systems used together provide the most reliable inspection, the magnetic system providing special assistance with defects located near the edges of the railhead. Recommendations for improving rail NDT include greater use of these two complementary systems (now available on only about 50 percent of U.S. rail test cars), greater attention to operator training and characteristics and to the inspection of new rail before installation, and changes in government regulations that will lead to more effective use of rail test cars. In addition, research is needed to relate defect growth to rail service conditions so that realistic decisions can be made about leaving defective rail in use. Developments leading to improved technology are also discussed.

The subject of nondestructive testing (NDT) of railroad rail is a complex one that involves technical considerations (such as types of inspection, the types and sizes of flaws that can be detected, and the reliability of detection), economic considerations (such as how often to inspect and the sizes of defects that should lead to rail replacement), and regulatory questions (such as how much leeway railroads should be permitted in inspection and rail replacement). Obviously, the performance of rail depends strongly on traffic density, axle loading, condition of equipment (flat spots on wheels, for example), and many other factors. This paper focuses on the technical aspects of rail NDT but also attempts to take some of these other issues into account.

Field NDT of railroad rail began in an organized way in the United States in 1928 with the introduction of a rail test car designed by Sperry (1). The NDT method used in this first car was an inductance method in which variations in the electromagnetic field induced by electric current in the rail were sensed by a pickup coil (2, 3). Since that early work, other magnetic and ultrasonic methods have come into prominence in the field inspection of railroad rails (4). In addition, eddy-current, liquid-penetrant, and magnetic-particle methods are used to assess new rails and/or repairs (5-7).

The use of these NDT procedures to inspect in-place rails has undoubtedly been of great benefit to the nation's railroads. In 1965, Magee of the Association of American Railroads (AAR) estimated that rail inspection saved the railroads almost $200 000 000/year by minimizing service failures and the costs associated with these failures (1). Although rail failures have not contributed in a major way to railroad fatalities, the inspection program has also saved lives.

There have been obvious benefits from rail inspection. Yet, in the past few years—as Figure 1 (8, 9) shows—there has been an increase in track-related accidents while other causes of train accidents have stayed about constant. Rail problems remain a significant factor (9). The number of defective rails found by NDT and replaced each year showed a dramatic rise in the late 1960s and early 1970s and now appears to have leveled off somewhat (10), in spite of the fact that total kilometers of track in the United States continues to decrease each year (11). We must also consider the increasing axle loading in recent years as 91-Mg (100-ton) cars have become more common [see Figure 2 (11)], and we must recognize that the increased loading on remaining rails may cause defects to grow at a faster rate. This means being alert to the possible need for detecting smaller rail defects or inspecting rails more frequently.

NONDESTRUCTIVE TESTING METHODS

Ultrasonic Testing

Ultrasonic inspection is normally done in a pulsed mode; some portion of the ultrasonic pulse is reflected or scattered back to a receiving transducer, sometimes the same transducer that transmitted the energy in the first place. The ultrasonic pulse travels at a known velocity in the rail [typically 5900 m/s (19 350 ft/s) for longitudinal waves]. Therefore, the time at which the reflected signal is received can be related to a distance in the metal rail. One can use electronic gates on the ultrasonic instrument to confine the inspection to a certain region, if desired. Typical ultrasonic frequency is 2.25 MHz.

Ultrasonic testing has many advantages for detecting cracks and similar discontinuities. A large part of the ultrasonic signal is reflected from such interfaces. However, if the receiving transducer is to receive a significant amount of the reflected energy, it must be in the correct location.

An easy flaw to detect is an extensive horizontal split head (see defect 1 in Figure 3) because an ultrasonic beam directed straight down the head toward the web and base will be reflected back toward the transducer. This same (0°) transducer also provides good inspection of the web area. Note, however, that, if the defect is a horizontal split head that does not extend over the web area (defect 2 in Figure 3) or a vertical split head (defect 3 in Figure 3), a transducer aimed straight down will probably receive only a very small reflection signal. To detect such defects by using ultrasound, it is necessary to use angled ultrasonic beams. Common angles, from the vertical direction, are 30°-60°, 37.5°, 45°, and 70°-80°. The capabilities of such angled beams for detecting common defects in rails are summarized in a report by Kaiser and others (12).

If the types of rail defects can be anticipated, the proper angular ultrasonic beam and the preferred location of the receiving transducer can be determined. In practical situations, however, there are some problems. For example, the transducers must be coupled to the rail in order to get as much ultrasound energy as necessary into and out of the rail. Two common approaches are to place the transducers in a liquid-filled rubber wheel or in sleds that slide along the rail. Liquid coupling is used between the wheel or sled and the rail. Both of these approaches impose some restrictions on the angular orientations and the number of transducers that can be used. Note that the curvature at the edges of the top of the railhead makes it necessary to place the transducers above a point near the center of the rail. This contributes to the difficulty of detecting defects located near the edges of the railhead. Defects located near bolt holes, rail ends, or welds also present problems because the reflections from these interfaces mask closely located defects.

Another significant problem is that of maintaining coupling while the test car is moving. Obviously, some

Figure 1. Train accidents by major cause (at inflated thresholds).

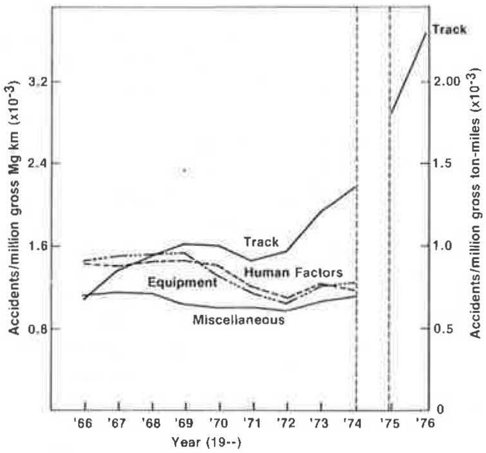


Figure 2. Average freight car capacity on U.S. railroads by year.

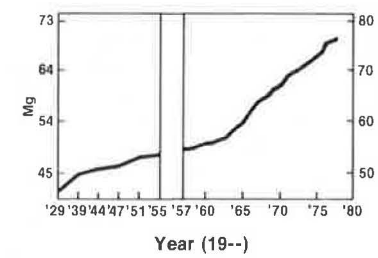
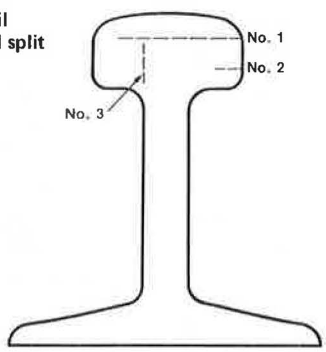


Figure 3. Orientations of several rail defects: defects 1 and 2, horizontal split heads; defect 3, vertical split head.



bounce is introduced. This can be checked for the 0° beam because the equipment should show a strong back reflection from the bottom of the rail base. For some of the angled beams, this is not the case, and coupling can be lost or become intermittent without the operator realizing it. In some cases, however, the angled transducers are deliberately located in the same coupling area as the 0° transducers to provide at least some indication of coupling.

Checking the sensitivity of rail inspection equipment is a significant problem. Ideally, one wants to adjust equipment sensitivity by using the same material and geometry as those of the object to be inspected. Naturally, it is difficult to carry a rail around and get it into position to test. A good sensitivity check would therefore involve something already in the rail. The Southern Railway System, for example, uses the reflection from bolt holes to set sensitivity. This seems to be a reasonable approach, but it does not work well for many of the angled beams. Certainly, the question of sensitivity adjustment merits further consideration.

Among other problems is the fact that surface defects, such as burns and shells, and welds often interfere with the transmission of ultrasound and therefore impede the detection of defects below those areas.

The presentation and interpretation of data are also important, of course. Most U.S. rail-car systems use pen recorders. The electronics system gates the return pulses so that only those pulses of interest cause pen deflection. A typical system described by Thomas and others (13) has two pens tied to a 0° ultrasonic transducer. One pen detects reflections in the head, web, or base of the rail; the other notes a loss of base reflection. In this system there are two ultrasonic transducers at 37.5° and one recorder pen is tied to each transducer. There are also two transducers at 70°, both of which are tied to a single recorder. The operator must watch the recorder pens (five in this case) and watch the track through an operator's window [see Figure 4 (14)]. If a suspicious signal is detected, the test car is stopped and the operator gets out to check the suspect area with a portable ultrasonic system. The hand check indicates either that the signal was a false alarm or that it was valid. In the latter case, some sizing of the defect is attempted.

Inspection speeds for rail test cars in the United States are in the range of 6-21 km/h (4-13 miles/h) (12, 15). Although inspection speeds in some other countries are reported to be as high as 100 km/h (62 miles/h) (12, 15), many foreign rail cars appear to operate in the 32- to 40-km/h (20- to 25-mile/h) range. In many of these cases, the inspection car does not stop to investigate; inspection data are recorded and analyzed later (15). In the United States, where rail cars stop to confirm and size defects, the average inspection speed is about 11 km/h (7 miles/h).

In some cases, a hand-operated ultrasonic unit, pushed along the rail by a walking inspector, is used to check rail (3, 7). These instruments are used to inspect areas that are not tested by the rail cars (switches, for example) and to go over critical areas such as rails associated with tunnels or bridges.

Magnetic Inspection

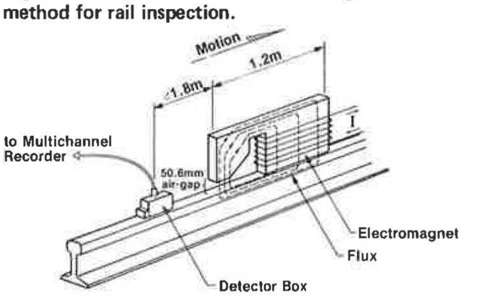
Two basic approaches are used in magnetic testing of rail. One is the inductance method used in the original rail test car by Sperry (1-3). In this method, current is put into the rail either by direct contact or by the movement of a strong magnetic field. Perturbations in the current flow that are caused by defects are detected by pickup coils. In the other approach, a magnetic field is set up in the rail. Flaws perturb the magnetic field, and variations in the residual magnetic field are sensed by a detector several meters away (to avoid detection of the active magnetic field). A diagram of a typical unit is shown in Figure 5 (13). This unit provides a longitudinal magnetic field, which yields good detection of transverse defects that would break the magnetic flux lines. In addition, magnetic fields are usually introduced across the railhead by following this unit with one that has a permanent horseshoe magnet whose pole pieces are at either side of the railhead. The resulting transverse magnetic field provides good detection of longitudinal defects.

Magnetic testing is usually limited to inspection of the railhead. Therefore, the number of rail defects discovered by using magnetic testing is generally less than the number found by using ultrasonics. Nevertheless, the two methods complement each other and are sometimes used together on the same test car.

The speed of magnetic inspection cars falls in the same range as that of ultrasonic cars; the higher speed

Figure 4. Ultrasonic rail test car used by British Railways (note operator in car window at right).

Figure 5. Diagram of AAR residual magnetic method for rail inspection.



Note: 1 m = 3.28 ft; 1 mm = 0.039 in.

of 21 km/h (13 miles/h) represents a magnetic system on good track. Kaiser and others (12) estimate that the speed capabilities of the electric-current or eddy-current methods can be as great as 80 km/h (50 miles/h) whereas the top speed for residual magnetic systems (systems of reasonable size) may be only about 27 km/h (17 miles/h).

Although coupling the magnetic field into the rail sounds simpler than what is required in ultrasonics, bouncing of the magnetic yoke and changes in the small air-gap structure on either end can lead to variations in the magnetic field that introduce false indications.

CURRENT PROBLEMS IN RAIL TESTING

NDT methods for rail provide signals that must be interpreted by the operator. Although a considerable amount of money has been spent on rail-testing equipment, it is less clear how much effort has been expended, on an industrywide basis, to ensure that operators are well trained and motivated. Since the operator is such a vital part of the NDT process, some additional industry effort would seem to be appropriate in this area.

The problem of operator performance is not unique to the rail industry. In fact, the nature of the problem is indicated by this quotation from a representative of an aircraft manufacturer, quoted by Robinson (16): "The burden is on the inspector to react on the spot and make a go or no-go decision on the basis of not altogether unambiguous information."

It is recognized that differences in the inspection equipment used by individual railroads present something of a problem in training operators. It is also recognized that the operator's motivation can outweigh technical training when it comes to the quality of inspection. Therefore, even if industrywide training of NDT operators is not pursued, research into the behavioral and psychological areas should be accelerated. It would be extremely beneficial to know what characteristics a good inspector should possess and how motivation can be maintained.

The NDT equipment currently available for rail testing is basically capable of performing the task, but one has to be aware of its limitations. In using ultrasonic equipment, for example, one depends heavily on the amplitude of a reflected signal. Yet, for several reasons, the amplitude may be low: If the defect is poorly oriented, the ultrasonic coupling is not good, or the calibration of the instrument is off, a low-amplitude signal can result. Since as many as six 70° ultrasonic transducers in a rail car are often tied to one recorder pen, it is entirely possible that one transducer may not be working properly. Yet this would not be known to the operator. Although we may not be able to do anything about poorly oriented defects, we can pay attention to calibration and coupling problems.

Some of the rail defects that grow in service undoubtedly stem from defects that were in the rail as delivered. Greater attention should be given to inspecting new rail to detect inclusions, piping, and similar defects that are likely to grow in service and lead to later rail replacement. Although this would not eliminate the defects that are caused by rail stresses, flat wheels, and other difficult conditions and thus would not eliminate in-service inspection, it would reduce costs for rail replacement in the field. It would probably also raise the average speed of rail test cars because fewer stops might be needed.

About 70 rail test cars are currently in use in the United States. About two-thirds of these are owned and operated by the railroads themselves (3), and the other third are owned and operated by the Sperry Rail Service (10). Except for one ultrasonic car used on the New York subway system, all of the Sperry cars use combined inductance-ultrasonic systems. Of the cars owned by U.S. railroads, about 10 percent are magnetic cars (residual magnetic method) and about 25 percent use combined residual magnetic-ultrasonic systems. The remaining 65 percent are ultrasonic cars.

In recent years, the use of ultrasonic inspection for rails has been emphasized. This is demonstrated by the preponderance of ultrasonic systems among the rail test cars and also by current development efforts in this area.

Nevertheless, the use of two complementary inspection systems is desirable. A combined ultrasonic-magnetic system appears to offer greatly improved defect detection (and signal interpretation) for the railhead. The additional use of the magnetic system offers more reliable detection for common railhead problems, such as vertical split and detail fractures. When these defects are located near the edges of the railhead, magnetic inspection is most useful. For other defects, particularly those located in the web or base of the rail, ultrasonics will continue to provide the best inspection.

It would appear that U.S. railroads are not testing rails as extensively as they could with currently available equipment and personnel. As indicated before, test cars typically provide an average speed of 11 km/h (7 miles/h). By taking 70 available cars and allowing each car to operate 8 h/day at 11 km/h, the industry could potentially inspect more than 6000 km (3600 miles) of track a day (by using only one shift). This translates into a capability to inspect almost 1.5 million km (0.9 million miles) of track a year. Certainly this would be reduced by factors such as track availability. Nevertheless, the actual number of kilometers of track now tested is probably considerably less than half that figure (10).

Although there may be some discussion about the numbers, there seems to be agreement about the conclusion that greater use could be made of available rail test cars. Part of the problem is certainly government regulation, in that railroads are compelled to remove defective rail quickly (often within 24 h) or drastically reduce train speeds. What often happens is that the rail test car is sent packing once it has located an amount of rail that can be replaced by the maintenance crews. A better approach would be to determine likely rates of flaw growth based on service conditions and to take this into account in the replacement schedule. It will require more extensive work, however, to relate flaw growth to anticipated stresses.

CURRENT DEVELOPMENTS

A few words about developments in progress in rail NDT may be appropriate to show the directions in which the industry is headed. Work has been going on for many years on electromagnetic transducers for ultrasound. A major advantage of these transducers is that physical contact with the object under inspection is not necessary and thus coupling problems are minimized. A great deal of work in this area has been reported in the Soviet Union, including potential application to problems of rail inspection (17). Development of electromagnetic transducers is now proceeding in the United States (18), and a test of these novel transducers for rail inspection is planned. In addition to ease of coupling, these transducers offer the potential for electronic variation of the angle of the ultrasonic beam.

The major developments directly associated with rail NDT are in the area of data processing and presentation. Investigators at the Transportation Systems Center (TSC) are working on a consolidated B-scan presentation that would present a cross-sectional view of the rail to the operator when a defect signal is detected and pinpoint the location of the defect (19). Other programs that are being pursued at TSC include an improved magnetic system to complement ultrasonic inspection and a fully automated rail test car that will have the capability for sizing defects. The British are also working on improved data processing. Their present system collects inspection data during night runs of the track. These data are later analyzed in a central location (15). New efforts in Great Britain are directed toward a completely automated system (20).

These appear to be representative of the major development efforts directly concerned with the detection of defects in rail by nondestructive evaluation. Other major problems, of course, are residual stresses and longitudinal forces in rail. These problems have particularly come into focus with the introduction of all-welded rail (21). This paper has not addressed that problem nor problems that are associated with nondestructive evaluation of welds.

Other developmental efforts that will possibly affect rail NDT involve ultrasonic testing and attempts to use portions of the signal in addition to, or instead of, ultrasonic amplitude. As indicated earlier, the amplitude of reflected or scattered ultrasound can be misleading. Current development work includes efforts to use spectral, phase, and other signal parameters to identify the type and approximate size of defects (22-24). These efforts should be followed.

CONCLUSIONS AND RECOMMENDATIONS

Rail NDT is strongly operator dependent, and the equipment has some limitations. Improvements in rail NDT could be made. The following are some near-term recommendations:

1. Pay more attention to the inspection of new rail; elimination of defects at that point can minimize more expensive problems in the field. However, it should be clear that in-service inspection would still be necessary.
2. Consider an industrywide training program for NDT operators. Not much attention appears to have been paid to the operator, a vital part of the present NDT system. At the very least, the railroads should join with other industries to help in determining the characteristics of a good inspector. Strong motivation is probably more important than textbook knowledge.
3. Take steps to be sure present equipment is functioning and the sensitivity is properly set. Adopt widespread use of cars that make use of two complementary NDT methods (ultrasonic and magnetic).

On a longer-term basis, the industry should move toward the following:

1. Work to help set reasonable government regulations and policies so that the full range of NDT capability can be used with minimum penalty. To do this realistically, more work will have to be done to relate flaw growth to rail service conditions.
2. Improve the presentation of NDT data to ease interpretation and minimize errors. On a longer-term basis, the industry should work for the development of more automated test systems. This is necessary if a significant increase in the speed of rail inspection is desired.
3. Develop improved techniques, such as ultrasonic methods in which coupling can be checked or the effects of coupling variations are minimized. Improved magnetic approaches, such as rapidly changing field directions, should also be factored into developmental planning.

These recommendations are made in an attempt to improve rail inspection and reduce the cost (both in terms of money and lives) of rail-related accidents. It is obvious that rail NDT has served the industry well in the past 50 years and will continue to do so in the future. But its impact can be enhanced if improvements are made along the lines suggested here.

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REFERENCES

1. G. M. Magee. Preventing Rail Failures in Track. Materials Evaluation, Vol. 23, No. 10, 1965, pp. 508-511.
2. Rail Defect Manual. Sperry Rail Service, Automation Industries, Danbury, CT, 1968, pp. 26-29.
3. The Track Cyclopedia, Section 9. Simmons-Boardman Publishing Corp., Omaha, 1978.
4. W. E. Chapin, R. Kins, H. C. Festel, and R. H. Breslin. A Bibliography of Rail Technology. Federal Railroad Administration, U.S. Department of Transportation, Rept. FRA/ORD-77/15, 1977.
5. J. Banks and D. C. Hansford. Examination of Surface Cracks in Carbon and Manganese Steel Rails by the Eddy-Current Technique. British Journal of Nondestructive Testing, Vol. 18, No. 6, 1976, pp. 174-179.
6. J. Banks. Magnetic Particle and Dye Penetrant Techniques as Aids to the NDT of Rails. British Journal of Nondestructive Testing, Vol. 15, No. 6, 1973, pp. 176-178.
7. A. K. Gurvich and others. Flaw Detection in Rails. Federal Railroad Administration, U.S. Department of Transportation, Rept. FRA/ORD-77/10, Dec. 1978.
8. W. H. Dempsey. Supplement to Statement on Railroad Safety to Subcommittee on Transportation and Commerce of the Committee on Interstate and Foreign Commerce, March 15, 1978. Assn. of American Railroads, Washington, DC.
9. A. E. Shulman and C. E. Taylor. Analysis of Nine Years of Railroad Accident Data, 1966-1974. Assn. of American Railroads, Washington, DC, Rept. R-223, April 1976.
10. AI Sperry Railer. Sperry Rail Service, Automation Industries, Danbury, CT, Vol. 47, No. 1, 1979.
11. Yearbook of Railroad Facts. Assn. of American Railroads, Washington, DC, 1979.
12. W. P. Kaiser, R. H. Byers, D. Ensiminger, H. C. Meacham, J. H. Flora, W. C. Bruce, L. Becker, and G. Posakony. Rail Inspection Systems Analysis and Technology Survey. Federal Railroad Administration, U.S. Department of Transportation, Rept. FRA/ORD-77/39, Sept. 1977.
13. J. M. Thomas, C. S. Davis, T. W. Rettig, and P. R. Bosinoff. Strategy and Methods for Cost-Risk Analysis of Defective Rail. Failure Analysis Associates, Palo Alto, CA, Rept. FAA-78-12-1, Dec. 1978.
14. Ultrasonic Eyes Aboard British Testing Train. Materials Evaluation, Vol. 29, No. 6, 1971, pp. 16A-18A.
15. W. D. Kaiser and R. H. Byers. Rail Flaw Inspection Technology. Paper Summaries, National Fall Conference of American Society for Nondestructive Testing, Denver, Oct. 1978, pp. 393-396.
16. A. L. Robinson. New Testing Methods Could Boost Air Safety. Science, Vol. 205, July 6, 1979, pp. 29-32.
17. V. V. Vlasov, V. A. Lanchak, N. A. Oluhkov, and I. V. Ivanov. Ultrasonic Method of Testing Railway Rail Tracks Using Electromagnetic-Acoustic Converters. Defectoskopiya, Vol. 3, 1971, pp. 94-98.
18. R. B. Thompson. New Electromagnetic Transducer Applications. Air Force Materials Laboratory, Wright-Patterson Air Force Base, Dayton, OH, Rept. AFML-TR-78-55, May 1978, pp. 340-344.
19. D. Lavery and H. Ceccon. State of the Art of Rail NDT in the U.S. Seminar on Railroad Nondestructive Evaluation, National Bureau of Standards, Washington, DC, May 15, 1979.
20. H. Jenkins. Track Maintenance for High-Speed Trains. AREA Bull., Proc. Vol. 77, No. 658, June-July 1976, pp. 511-513.
21. J. J. Yavelak and C. N. Scott. Requirements of Residual Stress Measurements Peculiar to the Railway-Freight Industry. Extended Summaries, Meeting of Society for Experimental Stress Analysis, Indianapolis, Oct. 23-25, 1978, pp. 17-18.
22. B. R. Tittman and R. K. Elsley. Experimental Measurements and Interpretation of Ultrasonic Scattering by Flaws. Air Force Materials Laboratory, Wright-Patterson Air Force Base, Dayton, OH, Rept. AFML-TR-78-55, May 1978, pp. 26-36.
23. L. Adler, K. Lewis, P. Szilas, and D. Fitting. Identification of Flaws from Scattered Ultrasonic Fields as Measured at a Planar Surface. Air Force Materials Laboratory, Wright-Patterson Air Force Base, Dayton, OH, Rept. AFML-TR-78-55, May 1978, pp. 36-43.
24. R. Shankar and A. N. Mucciardi. Application of Adaptive Learning Networks to Ultrasonic Signal Processing: Detecting Cracks in Stainless Steel Pipe Welds. In Ultrasonic Materials Characterization (H. Berger and M. Linzer, eds.), American Society for Nondestructive Testing, Columbus, OH (in preparation).

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Review of Rail Research on British Rail

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The rail research program of British Railways, which is aimed at understanding and reducing the severity of various mechanisms of rail failure, is described. An important part of the work is the measurement and prediction of rail stresses and the study of force-free temperature for continuous welded rail. To reduce failure problems, it is necessary to develop laboratory-based techniques to assess the performance of rail steels and welds. This requires a knowledge of the dynamic and static stress environment of the rails and computer programs to calculate these stresses. The study of failures includes the study of Thermit and flash-butt weld failures, tache ovale defects, star cracks at bolt holes, and squat defects. It has been found that the majority of Thermit weld failures can be attributed to poor welding practice. Flash-butt weld failures are much less frequent but may become more of a problem as the more wear-resistant rail steels are introduced into welded track. The need to develop better steels for switch and crossing work has provided an impetus to develop a weldable austenitic manganese steel and also bainitic steels of high strength and toughness. These developments are reviewed.