

though some problems remain in this fatigue-test method in view of actual track conditions, the head-hardened rails exhibit fairly higher fatigue-strength values than those of the as-rolled rails of the nearly same tensile strength. This difference is caused not only by residual stress but also by surface conditions, e.g., surface roughness. The rotating bending fatigue strength measured on cut-out specimens that are free from residual stress and surface conditions is proportional to their tensile strength and can be expressed by the following equation, as with other steels:

$$\sigma_w = 0.646 \times (\text{tensile strength}) - 227(\text{MPa}) \quad (3)$$

Therefore, the importance of residual stress in fatigue strength should always be taken into consideration.

As stated above, this head-hardened rail satisfies most of the requisites for high serviceability. The wear behavior of this rail in actual tracks is as follows. Figure 18 shows the wear on the gauge side of high rail under an axle load of 22-25 tons and traffic tonnage of about 40 million gross tons (MGT). The maximum wear of the gauge corner is less than one-third of that of standard carbon-steel rail. Figure 19 also shows the wear on the gauge side of high rail under an axle load of 25 tons and traffic tonnage of about 200 MGT. The maximum wear of the gauge corner is about 5-7 mm and surface defects are hardly observed except for some flakings on the running surface. Low side rail exhibits little metal flow.

At the beginning of production, it was not necessarily intended that this rail satisfy the above-mentioned requisites, but this rail seems to possess high serviceability for heavy-load railways and has exhibited good performance in many railways. Remaining problems, if they exist, will be in welding and corrugation.

CONCLUSION

As the result of investigations into the requisites

for rails of high serviceability, increasing the strength of rails through the refining of pearlite, compressive residual stress, and austenite grain refinement has proved to be effective in prolonging the service life of rails. One type of rail that satisfies these requisites is the head-hardened rail, which possesses a tensile strength that exceeds 1200 MPa, a very fine pearlitic microstructure, and a compressive residual stress of about 400 MPa in the hardened zone. This rail has exhibited good performance with less wear, fewer defects, and less metal flow in many heavy-load railways.

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Rail Manufacture in Great Britain

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A review of the history of rail manufacture in Britain, together with current and future plant and process routes, is presented. British capability to meet current and predicted future rail requirements is associated with modern steelmaking process routes, specialized rail manufacturing plants, long experience in supplying the varied needs of railroads internationally, and a market-oriented management philosophy. Current American dimension requirements present no problems, as routine manufacture meets stricter British and European standards. The continuous casting of rail steel and the prohibition of aluminum deoxidation are claimed as major factors that limit the size and number of complex alumino-silicate inclusions in the production of clean rail steels. Other process-route parameters also contribute. Future rail requirements of a metallurgical nature (e.g., clean, low-hydrogen steel) and of a geometric type (e.g., better section and straightness control) are discussed. The urgent need for better track and vehicle maintenance standards is strongly emphasized. The large American rail market and the considerable standardization of rails could be expected to encourage specialization and development of advanced rail-making technology. Low home-market rail prices and limited involvement in more sophisticated international rail markets may have inhibited such developments.

The evolution of, and advances made in, rail technology have resulted in more stringent requirements being incorporated in many rail specifications. Metallurgical, mechanical, and geometric aspects are now of greater importance than in the past due to more severe rail track and traffic conditions, e.g., the use of higher axle loads, increased traffic speeds, the adoption of diesel or electric traction, and the use of continuously welded track.

The ability of the rail manufacturer to meet the more stringent requirements is affected, to varying degrees, by a number of factors, which include the following:

1. The processes used and plant available for steelmaking, casting, rolling, and finishing of the rails;

2. The overall experience of the manufacturer in rail production; the range of rail sections, rail steel grades, and rail specifications produced; and the level of experience in meeting stringent rail-specification requirements; and

3. The priority given by the manufacturer to rail production and the quality and reliability aspect of the product, which should be evident in the extent of the technical support provided to both rail manufacture and the rail market and the quality control and assurance systems employed.

An outline of the past history and current situation of rail production in Great Britain provides the background for later comments that relate to the four specific aspects of rail technology chosen for this study.

HISTORICAL BACKGROUND

Steel rails have been produced in Great Britain for more than 100 years and, throughout this century of experience, a high proportion of this production has been exported to most countries in the world. In the past, many railways ordered to their private rail specifications and, even today, despite the emergence of internationally accepted rail specifications [e.g., British Standards (BS), American Railway Engineering Association (AREA), and Union Internationale des Chemins de Fer (UIC) specifications], there are still many railroads that order to their own specifications. Thus, significant participation in the rail export business involves the manufacturer in the disciplines of both flexibility and control to meet the various market requirements.

More than 50 years ago in Great Britain there were 15-20 steel plants and rolling mills that produced rails. Steelmaking processes included acid Bessemer, acid, and basic open-hearth plants, all of which produced a "semikilled" or "balanced" steel that was directly teemed into open-topped ingots. In most cases the ingots were rolled to rail in a "single heat" (i.e., hot ingots charged in soaking pits and furnaces and rolled directly to rail). In a few cases, an intermediate heating of the rolled bloom was employed, i.e., "rolling in two heats". In virtually all these works, the rails were produced in multiproduct rolling mills where structural sections, blooms, billets, etc., were produced in addition to rails. Thus, rail production at individual works varied from being the major product to that of being a minor item, where rail contracts were accepted merely to balance order load and mill capacity.

In recent decades, and particularly since nationalization of the British steel industry and formation of the British Steel Corporation (BSC) in 1967, there has been considerable rationalization of production. Rail and track products rolling and finishing are now concentrated at the Workington Works of BSC Track Products, which now specializes entirely in the production of rail and smaller tonnages of track accessories (e.g., joint bars, tie plates, and steel ties).

RAIL PRODUCTION AT WORKINGTON WORKS

The Workington Works of BSC (formerly Workington Iron and Steel Company, a branch of the United Steel Companies) is situated on the northwest coast of England, with private rail access to the Workington seaport, which is capable of handling 10 000-ton ships. The Workington Works celebrated 100 years of steel-rail manufacture in 1977, and rail, throughout its long history, has been the major, top-priority product.

Up to 1974, Workington Works was a fully integrated plant that converted hematite hot metal (pig iron) into steel by the acid Bessemer process (two 25- to 30-ton vessels) and also by using a single 25- to 30-ton basic electric-arc furnace for rail-steel production. The rail steel was direct teemed (or top poured) into open-topped semikilled ingots, which were then hot charged into gas-fired soaking pits and rolled to rail "in one heat".

This practice had been very satisfactory for the production of normal grade rails, but it was recognized in the late 1950s that the trend in rail markets would, in the future, demand the supply of a larger proportion of higher-strength rails. The relatively small demand for high-strength rails in the late 1950s was satisfied at Workington by the production of fully killed, acid Bessemer steel, direct teemed (top poured) into hot-topped (feeder-head) ingots or, alternatively, in manufacturing fully killed, bottom poured (uphill teemed), hot-topped ingots from the basic electric-arc furnace.

In order to meet future requirements, Workington Works in 1958 commenced trials with fully killed, hot-topped ingots produced at other works in basic-oxygen furnaces (BOFs). These trials proved the suitability of BOF steel for rail manufacture.

In 1962, trials with continuously cast (CC) blooms for rail manufacture commenced and continued for several years to establish the optimum continuous casting and subsequent rolling parameters for the potential new process route and to fully evaluate product quality. This work confirmed that the CC process had tremendous potential for the improvement of rail quality, with respect to both surface and internal quality. In 1970, the decision was made to eventually close the Workington acid Bessemer and electric-arc steel plants and to concentrate all rail rolling and finishing at Workington, the required steel to be supplied from the modern basic-oxygen steelmaking and bloom CC plant at Lackenby, Teesside. This decision was implemented in July 1974.

CURRENT RAIL MANUFACTURING PROCESS ROUTE

Steelmaking

Rail steel is produced at the BSC Teesside Works Lackenby BOF plant equipped with three 260-t vessels. Oxygen blowing is terminated at a minimum turn-down carbon level of 0.1 percent, and employs instrument and computer control. Turn-down carbon levels lower than 0.1 percent are not favored in order to avoid high oxide levels in both metal bath and slag that militate against the good control of steel chemistry and cleanliness. Deoxidation, recarburization, and alloying take place during tapping from the converter into the steel ladle. A fully silicon-killed steel is produced and, in order to prevent subsequent ladle-nozzle blockage problems during CC and also to avoid the production of undesirable alumina and complex alumino-silicate inclusions in the steel, the use of aluminum in deoxidation is prohibited.

After tapping the BOF and prior to CC, the steel ladle is transferred to a gas flushing station where the steel is gently stirred by using an inert gas (i.e., argon or nitrogen). In addition to ensuring uniformity of metal temperature throughout the ladle, the stirring action assists in homogenizing the chemical composition, permits a limited amount of steel analysis trimming, and also encourages the flotation of inclusions and deoxidation products into the slag; i.e., the gas flushing operation contributes to the production of more uniform and cleaner steel.

Twin sliding gate nozzles in the steel ladle ensure the pouring of slag-free metal into two tundishes, each feeding four casting strands. Specially selected refractory and thermal insulating lining materials are used in ladles and tundishes to minimize erosion and thus achieve higher plant availability and security; in addition, the use of these high-quality refractories minimizes the danger of pick up of exogenous inclusions in the steel. The tundishes maintain a constant ferrostatic head during casting.

In addition, the metal streams--from ladle to tundish and from tundishes to CC molds--are contained in special refractory tubes to protect the liquid streams from the atmosphere in order to minimize the pick up of oxides and undesirable gases by the liquid steel. Slag powder mold lubrication is employed. Shrouding of liquid steel streams and the submerged pouring practice has been adopted as standard practice in recent years for the casting of higher-strength rail steels (e.g., AREA and wear-resisting grades) and for alloy-grade rail steels. Normal grade (i.e., lower-strength) rail steels continue to be continuously cast by the previously reported open-pour process that employs oil as the mold lubricant.

After CC and cutting to ordered length and weight, the hot rail-steel blooms of AREA and the wear-resisting and alloy-rail grades are charged into specially insulated containers, and cooling is retarded in the temperature range of approximately 600-450°C over a period of at least three days when temperature loss is 1.5°C/h, maximum. This bloom cooling (BC) procedure is controlled to ensure adequate removal of hydrogen, which guarantees that the rails subsequently produced will be free from shatter cracks.

Liquid-steel vacuum-degassing equipment will be installed during 1982. Each bloom is fully identified and after cooling is transported about 120 miles by rail to BSC Workington Works. The standard CC bloom cross section used for rail production is 330x254 mm in lengths up to 24.5 ft designed to produce a multiple of ordered finished rail lengths.

Ingot Steel

A small proportion of Workington rail production is based on the use of similar-sized blooms rolled from ingots of basic-oxygen or electric-arc steel. This secondary steel supply source is also based on the use of fully silicon-killed steel with nil or very restricted use of aluminum deoxidation, hot-topped (feeder-head) ingots, and preferably bottom-poured ingots in order to come as near as possible to the high-quality standards achieved in the primary steel supply route (i.e., BOF and CC blooms).

Rail Rolling at BSC Workington

When blooms are received at Workington they are marshaled in the bloom stockyard to be rolled against specific orders. The rail rolling process route consists of the following:

1. One large modern five-zone, natural-gas-fired, bloom reheating furnace;
2. One 42-in blooming mill, which is now used as a bloom-sizing mill, where in about four or five passes the standard CC bloom cross section is reduced to that appropriate for the rail section and size being rolled;
3. One bloom shear for merely trimming the sized bloom end to facilitate entry into subsequent roll stands;
4. One 32-in roughing mill where generally in

five passes the rough rail shape is formed; and

5. One 28-in finishing stand where generally in four passes the final rail shape is produced.

Both mills are operated as two high stands and the rail-roll design adopted is invariably based on the diagonal roll-pass design, which provides better control of the mechanical working of the steel in the profile and also of the cross-section dimensions, as compared with older conventional roll-pass designs.

The effective barrel lengths of the roughing and finishing mill rolls at 7.0 and 6.5 ft are relatively short, compared with multiproduct mills that produce both structural sections and rails. The shorter roll barrel length results in less spring (deflection) in the rolls when under load while forming the steel to profile, and hence contributes toward achieving good control of rail cross-section dimensions.

Rolling rates on heavy rails average 120-130 tons/h, which is a rapid tempo that assists in achieving uniformity of temperature and rolling conditions in a cross-country mill of relatively small area. The short floor time reduces heat losses, assists in the control of section accuracy, and reduces the depth of decarbonization on the rail surface. Each bloom weight is designed to produce a multiple number of the customer's standard rail length, the maximum mill run-out length being approximately 250 ft.

Rail Finishing

Currently, the rail finishing department has been restricted to the cold finishing (straightening, cutting, and drilling) of rails of a maximum length of 60 ft. Thus, the 250-ft rolled length is hot sawn to the customer's length plus cutting margin (61 ft, maximum), and then passes to the cooling beds. Any rails that require controlled cooling (i.e., where blooms have not been controlled cooled) are charged by crane into insulated cooling boxes for hydrogen removal treatment.

The cold rails (at 60°C maximum temperature) are then roller straightened on one (of two) seven-spindle roller-straightening machines, the two machines being of different ranges of spindle centers and straightening load capacity. The small machine with spindle centers of 50 in straightens rails from 50-113 lb/yd and the larger machine with 60-in spindle centers is used for 113 lb/yd and heavier sections. Any end or general-line straightness correction that is required is done by using two-directional hydraulic presses (two machines being available). Rails are then accurately cold sawn to length and bolt holes drilled by using four modern high-speed carbide-tipped sawing and drilling machines.

A comprehensive range of quality control and quality assurance (QA) procedures are routinely applied to all operations involved in handling a customer's order. The codes of practice and operating procedures involved in office routines in processing an order from inquiry to dispatch of the product--in design, tooling, manufacture, inspection, and testing--are detailed in manuals, readily available to all personnel involved. These QA procedures have been subjected to detailed examination and assessment by the skilled QA assessors of both British Rail and the British Ministry of Defense and have been officially approved. Both groups of assessors regularly and separately make further audits of the Workington Works QA system. Currently, virtually all heavy rails more than 113 lb/yd are subjected to automatic in-line ultra-

sonic testing; the lighter rails are checked by using manual portable ultrasonic test units.

A completely revised rail finishing layout is nearing completion and is due to be commissioned in spring 1982. The new process line will commence at the hot saws where the as-rolled 250-ft rail length will be hot sawn to approximately 125 ft in length and allowed to cool on new, wider cooling beds. When cold (below 60°C), the rails will then be roller straightened directly from the cooling beds and all rails will be passed through the automatic, in-line, ultrasonic testing machine. Thereafter, the straightened 125-ft (approximate) lengths will be accurately sawn to a customer's order length and bolt holes drilled, when required, by using high-speed carbide-tipped saws and drills.

Whereas the new rail finishing facility will enable Workington to supply longer rail lengths (up to a maximum of 120 ft), the main objective of the installation is to achieve improved control of rail straightness (both end and general-line straightness), more uniform rail section dimensional accuracy, and reduced handling (thus less risk of mechanical damage to the rail surface). References to the impact of this new rail finishing layout will be made later in this paper.

DIMENSIONAL ASPECTS

A comparison of the section dimensional tolerances of the three major internationally accepted rail specifications shows that the British standard (BS11) has tighter tolerances than AREA and UIC specifications in most cases. Generally, the differences between BS and UIC tolerances are due to the former being designed and "toleranced" in imperial (inch) units whereas European section designs and tolerances are in metric units.

However, AREA section dimensional tolerances are generally much more generous than BS and UIC specifications. The BSC Workington Works has a long history of working to British and also UIC rail specifications and, as outlined elsewhere in this paper, the combination of equipment, experience, and refined QA procedures enables Workington Works to fully meet AREA cross-sectional dimensional tolerances without any problems.

Also, AREA straightness, end squareness, rail length, and bolt-hole tolerances create no problems since they are generally wider than British normal procedures, which are geared to meet BS and UIC standards. The tight UIC rail-length tolerances have created some minor problems in the past when Workington's end-finishing equipment consisted of old rotary milling machines. Such orders necessitated the application of stricter supervisory and quality control measures. The recent introduction of high-speed carbide-tipped saws has considerably improved length control, and research work to achieve even better length control is in process. It is questionable whether the tight UIC length tolerances (0.08 in) are necessary for continuously welded rail (CWR) and, indeed, in BS a length tolerance of ± 1 in is permitted for CWR. Also, British experience has been that ± 0.19 in is an acceptable length tolerance for jointed track.

Rail verticality and asymmetry are not mentioned in AREA specifications, but they are in BS and UIC specifications. When this requirement was initially introduced some years ago, manufacturing control problems were experienced but, by diligent investigation of the contributory causes and application of quality control procedures, this aspect now causes no problems. Indeed, the rails produced at Workington have been shown in a recent comparison with other European makers to have an exceptionally high

standard of verticality and asymmetry.

Rail-end straightness requirements in AREA specifications are much more generous than BS11 or UIC specifications. AREA permits the use of a 3-ft straight edge with maximum ordinates of 0.025-in vertical and 0.030-in horizontal, whereas BS11 and UIC specify 5-ft straight edges with 0.031-in maximum ordinate in both planes. By assuming smooth curves at rail ends, the comparison of acceptance ordinate limits based on using a 5-ft straight edge are as follows:

	AREA (in)	BS11 and UIC (in)
Ordinate		
Vertical	0.069	0.031
Horizontal	0.083	0.031

Meeting AREA standards is therefore no problem, given BSC's past and current experience of operating to BS11 and UIC specifications.

Roller straightening of rails has been used at BSC Workington since 1946. Both available machines are primary straighteners that operate in the major axis (xx), i.e., with roller contact on the central part of the rail head and foot. There is sufficient plasticity induced while loading the rail in the major axis to enable some correction of straightness in the minor axis to be made by the roller collars. Whereas most rail-roller-straightener machine manufacturers offer two-stage rail-roller straighteners, i.e., a smaller secondary machine with rollers that engage in the rail fishing chambers to straighten in the minor (yy) axis, BSC does not consider the marginal advantages that may be derived justify the capital and operating expenditure involved.

Advantages of Roller Straightening

There are several advantages to roller straightening of rail. Some of these are as follow: (a) a highly productive and less labor-intensive operation; (b) an in-line operation, which is suited ideally to the straightening of long rail lengths; (c) less handling of the product and therefore less risk of mechanical damage; (d) a markedly superior straightness standard is achieved (where deviations do occur, these tend to be smooth curves rather than the angular "dog legs" frequently produced by traditional pressing); (e) a reproducible operation, less dependent on an operator's skill and subjective standards; and (f) the residual stress pattern in the roller-straightened rail must be more uniform along the rail length than in pressed rail.

Disadvantages of Roller Straightening

The disadvantages of roller straightening include the following:

1. Marginal section dimensional changes occur in the roller-straightened rail due to the compressive bending action, plastic deformation, and redistribution of internal stresses. However, the leading and trailing ends of the rail, for a distance of half the machine roller pitch (25-30 in), are affected little and remain almost at as-rolled size. The dimensional differences between the unaffected ends and the main roller-straightener affected rail length are dependent (to varying degrees) on the rail-steel grade (yield strength), the roller-straightener practices (applied loads and deflections), the rail section design, and the straightening-machine design.

Typical examples of cross-section dimensional changes on normal grade rails are as follows: loss of rail height = 0.025 in, increase in foot width =

0.025 in, and increase in head width = 0.006 in. Of the rail height loss, about three-quarters (0.018 in) appears as tightening of the fishing, and one-quarter (0.007 in) in flattening of the head crown running surface. The sectional dimensional changes are normally smaller with higher-strength rail steels.

2. Entry into the straightening machine rollers causes a small deformation (batter) at the extreme running surface leading end. Thus, a small amount (say 0.38 in) must be cut off the rail end. This is essential if the rail is being used for jointed track, but it is conceivable that this condition may be acceptable for welded track.

3. Tooling is more costly than for traditional pressing since each rail section requires at least one set of rollers.

4. Incorrect machine roller setting or operation is likely to result in a number of inadequately straightened rails. However, machine adjustment and correction can normally be readily made, given sufficient experience.

5. Machine roller damage or accumulation of mill scale can result in repetitive cyclic abrasion or imprinting of the rail surface. Such mechanical damage is readily seen, and the operation must be stopped immediately for corrective action. However, this mechanical damage can result in the affected rails being scrapped as unsafe for service if notching is severe.

6. The roller-straightening operation markedly alters the residual stress pattern and levels in the rail as compared with the as-rolled unstraightened rail. However, this internal residual stress pattern should be relatively uniform as the majority of each rail has been subjected continuously along the length to the same bending and cold-working operation, as compared with the intermittent application of traditional pressing.

Whereas most railways insist on the superior straightness quality standards obtained by roller straightening, there is some concern about the residual stress levels and their potential contribution to increased fatigue, more rapid crack propagation, and, ultimately, brittle fracture. However, the initial service and work hardening of the running surface counteract the tensile residual stresses in the zone of most concern to track maintenance engineers.

7. There is increasing evidence that roller straightening may be a major contributor to the production of long wavelength undulations on the rail running surface [wavelengths equal to the roller circumference (say, 66-80 in) and amplitude of 0.020 in]. Such long wavelength undulations have caused concern to some European railways that operate very high-speed passenger traffic and, hence, there is some pressure to establish limiting acceptance criteria. In BSC's experience, this feature can be kept under control by close attention to roller-straightening machine maintenance and close control of fits and alignments.

BSC Workington has a long experience with, and intends to continue the use of, rail-roller straightening, which to date is the only feasible and economic production method to achieve the high straightness standards expected and required by most railroads. The inevitable change in rail section dimensions can be limited by due care and control in the straightening operation. Rail section dimensions are generally checked at the rail ends, due to the importance at rail ends of section profile accuracy for both jointed and welded track. The marginal changes in section dimension in the main part of each rail length are considerably less than

the permitted tolerance ranges and are also generally within the dimensional tolerance ranges of associated fittings and fastenings. These generally do not give reason for concern even if the affected portion may on occasion be slightly outside a particular dimension minimum or maximum tolerance. Should it be essential that the complete rail length be strictly within all dimensional tolerance limits, then the rail section concerned will be rolled either to tighter tolerances or to an amended tolerance range to cater for subsequent roller-straightener effects. Another alternative is to cut off the roller-straightener unaffected ends. All these procedures are feasible with BSC's new rail finishing plant and its established QA procedures, but involve additional manufacturing cost, and such policies will only be adopted when necessary by prior agreement and price compensation.

Other disadvantages of roller straightening can be dealt with by care and discipline in the control of the operation, such as the following:

1. End batter--removed in high-speed sawing to length;
2. Tooling costs--maximizing roller life by material selection and judicious use and dressing of rollers;
3. Production of batches of inadequately straightened rail--established machine setting and adjustment practices and the application of QA procedures; and
4. Repetitive surface damage--by discipline in operation.

The residual stress problem is minimized by care in both rail cooling after rolling and in setting up the roller-straightening machine. The objective is to minimize the internal stresses in the unstraightened rail by the application of standardized cooling-bed procedures. Thereafter, during roller straightening the deflections and loadings applied must be sufficient to ensure the production of a good straightness and yet minimized to avoid the production of high residual stresses.

NONMETALLICS AND STEEL CLEANLINESS

The production for general application of a classification of steelmaking and casting parameters in relative order of their importance that affect the number and size of complex alumino-silicate inclusions is extremely difficult. The overall process route at each manufacturers' works must be considered, as the policy and practice adopted with respect to one parameter may be either compensated for or aggravated by that adopted with respect to another parameter.

It is the policy of BSC Track Products to eliminate or minimize the presence of alumina and complex alumino-silicates by tackling the problem at the source by deliberately avoiding, or in ingot production severely restricting, the use of aluminum in deoxidation. However, BSC accepts that clean steel can be produced by the use of aluminum deoxidants but the success may depend on other steelmaking and casting control practices adopted. The physical control of the addition of aluminum to liquid steel does present some severe practical problems, which can result in variable results; thus, BSC prefers to avoid such problems and insist on the use of silicon-killed steel.

The study of complex alumino-silicate inclusions cannot be divorced from general steel cleanliness; thus, the following comments deal with both aspects. Also, the subject is discussed in chronological order of steelmaking and casting, rather than rela-

tive order of importance, bearing in mind the previous statement that it is the overall process route that is most significant.

Modern fast steelmaking processes are preferred for rail steel manufacture. The high rate of carbon removal and associated bath turbulence encourage the production of cleaner, lower-gas-content liquid steel. Thus, the BOF process is preferred rather than the slower, basic open-hearth process.

In theory, the termination of decarburizing at near-finished steel carbon specification should produce lower oxide contents and cleaner steel. However, overall steel-composition control is very important and it was found that the best compromise is to aim at a turn-down carbon content of 0.10 percent in the BOF process.

Temperature control during steelmaking has a major influence on the gas and oxide content of the bath. A successful continuous casting practice is dependent on good steel temperature control, the CC process being less tolerant of temperature variations than conventional ingot casting practices. Thus, the use of CC imposes a stricter temperature discipline on the steelmaker and contributes to better steel cleanliness.

Comparison of BSC's previous semikilled rail with current fully silicon-killed rail steel confirms its opinion that the former process (semikilled open-top ingot practice) is no longer acceptable for the production of high-quality rails. In addition to excluding the use of aluminum, BSC also regularly reviews the ferro alloys used and avoids the use of any batches of above-normal aluminum content. The production of rail steel in newly lined convertors and steel ladles is also avoided since deleterious alumina, inclusion, and gas pick-up can occur.

Ladle flushing with an inert gas prior to CC produces more uniformity of metal temperature and chemical composition; it also assists in more uniform mixing of deoxidants and recarbonizers and the coalescence and flotation of solid-liquid deoxidation products, thereby contributing to cleaner steel.

There are various features associated with the BSC CC process, some of which are necessary for successful operational control, which also contribute toward the production of cleaner steel and smaller inclusions, as outlined below:

1. The use of special high-quality refractories in ladles and tundishes reduces wear and the pick-up of exogenous inclusions.

2. Pouring via tundishes maintains a constant ferrostatic head above the metal streams pouring into the CC molds (i.e., more uniformity in pouring speed). Also, the tundishes give the opportunity for further slag and inclusion separation from the metal.

3. Shrouding of the ladle to tundish streams protects the metal from exposure to the atmosphere. Lack of such protection can result in a marked increase in the metal oxygen and gas content. In addition, submerged tube pouring from tundish to molds prevents further exposure to the atmosphere.

4. Inherent in the CC process is the absence of risk of deleterious materials that fall into molds or adhere to mold walls--a serious risk in ingot practices.

5. The controlled rapid cooling of the smaller cast cross sections used in CC markedly reduces the solidification period and hence the opportunity for segregation and coalescence of inclusions. Thus, combined with the previously noted CC features that contribute to the reduction of the total inclusion content, the rapid solidification process assists in minimizing the risk of large inclusions.

6. The casting speed and cooling water-flow rates

and various other parameters in CC can be readily controlled and adjusted to maintain a high standard of surface and internal bloom quality.

Some inclusions are inevitably present in all steels, no matter how clean, and hence it is BSC's aim to ensure that these are of the least objectionable type. BSC aims to produce calcium manganese silicates that, when present in the product, will be of a rounded, nonangular shape. This inclusion type is more readily self cleansing, it floats into the slag more easily, and when present in the solid steel is less injurious. The shattered clusters (often experienced with complex alumino-silicates), which under stress can unite and act as a single very large inclusion and stress raiser, are not experienced with calcium-manganese-silicate inclusions.

Also, BSC's low-aluminum content ensures that the sulfides present are of the least injurious, non-angular type. Although high sulfur and sulfide contents are avoided for rail steel, it is BSC's policy to avoid ultra-low sulfur levels and maintain sulfur and sulfide levels sufficient to minimize hydrogen and shatter-crack problems.

The use of rolled blooms "ex" ingots is a very minor steel supply route for rail production at Workington. Similar control principles are applied to those stated above for CC steel. The policy is to use fully silicon-killed steel, bottom poured into feeder-head (hot-top) molds of proven and acceptable shape and design.

In addition to the control of these steelmaking and casting parameters, BSC considers that a routine cleanliness assessment of the rails is essential for efficient quality control. Multiprobe (16 probes) ultrasonic testing equipment, specifically designed for rail testing by BSC research and technical departments, is applied to obtain the routine general cleanliness assessment of all rails. The data are used mainly as a feedback into the QA and quality control system, rather than merely as an inspection and acceptance/rejection tool.

SERVICEABILITY

In considering the features required of rails in the future, one must question the future service conditions, track standards, and maintenance-of-way standards. Some ideas on the future rail requirements in an environment of 100- to 125-ton freight cars, which represent axle loads in the range of 33-40 tons, will be discussed. There have been various comments in recent years in the technical press and at conferences questioning the wisdom of adopting 125-ton cars, alleging that the track and car maintenance costs escalate so rapidly as to outweigh any potential operating cost advantages. Thus, one must raise the question as to whether or not the adoption of heavier freight cars (with axle loads of 33-40 tons) is inevitable and advantageous economically.

A comparison of the maximum axle load, rail section weight, and tensile strength used by various railways raises various queries (see Table 1). Why can British Rail use a lighter rail section and lower tensile rail steel than European continental railways, despite their higher maximum axle loads? The North American railroads, with higher axle loads, use both higher tensile strength rail steel and much heavier rail sections. Is this necessary? In supplying United Kingdom (U.K.) steelworks that operate very heavy axle loads of 51-74 tons, BSC has experienced most problems at the site that uses the lower (i.e., 51 tons) axle loads. The factors, some of which cannot be quantified, that result in these

Table 1. Comparison of axle load, section weight, and tensile strength of various railways.

Railway	Maximum Permitted Axle Load (tons)	Rail Section Weight (lb/yard)	Grade of Rail, Minimum Ultimate Tensile Strength (psi)
European continental railway	24.3	121	128 000
British Rail	27.5	113	103 000
North America	33-40	132 + 136	128 000 ^a
U.K. steelworks	51-74	113	156 000

^aPlus some 156 000 psi.

differing rail requirements are associated with other track, traffic, and maintenance aspects.

Thus, in addition to questioning future axle loads, one must also question future policies that relate to track and maintenance conditions. It is difficult to quantify in economic terms the differences in problems experienced by badly maintained railroads with those of well-maintained railroads (maintenance in this context includes vehicles and wheels in addition to maintenance-of-way). Nevertheless, BSC's experience as a rail supplier to railroads throughout the world confirms that experiences differ markedly and that in the best conditions the metallurgical properties possessed by the rail will be less important than with a badly maintained railroad.

Taking account of the variability of railroad operating and maintenance standards, and assuming that the rail section selected (used) is of adequate beam strength, then there would appear to be two main types of requirement for rails in the future--metallurgical and geometric.

Metallurgical Requirements

The rail steel must be of adequate tensile and yield strength to withstand contact stresses; the metallurgical structure at the running surface must be capable of withstanding considerable cold work without exhibiting excessive wear or developing fatigue failure. The rail-steel chemistry and process route will determine the tensile properties--hardness and metallurgical structure. Although some research work is in progress throughout the world on different metallurgical structures, it is BSC's opinion that, from both technical and economic aspects, a fine pearlitic structure will remain the optimum.

However, as wear resistance and rail life increase, resistance to fatigue damage becomes increasingly important, and it is predicted that rail steel cleanliness in all steel grades and tensile strengths will be a future focus of attention. In addition, the need for stricter control of steel hydrogen content will be important, as the type and number of inclusions present can affect the tolerance level for hydrogen of the rail steel, which is of particular importance if rail life increases.

Whereas all current rail steels have an inherently low notch ductility and fracture toughness, this appears to be an inevitable compromise in order to achieve adequate wear resistance. Most railroad engineers have learned to live with the low fracture toughness of rail steels; thus, future trends are likely to be an extension of current policies, namely to minimize the initiation and propagation of surface or internal cracks.

It is considered that the rail suppliers' contribution will be to ensure the elimination of surface and subsurface defects and produce uniform internal quality by minimizing segregation inclusions and hydrogen. Rails of the future must also be capable of being handled and transported, welded,

repaired, and machined by routine, standard techniques. Under good track and traffic conditions, it is expected that the present standard AREA rail grade will continue to have wide application if produced according to the best up-to-date manufacturing practices. However, there are likely to be some extensive demands for an improved carbon rail for more onerous applications.

Likewise, the trend toward the increased use of premium grade rail steels for very severe service conditions is likely to continue. The current attempts to meet the demands for premium grade rails include the use of fully heat-treated carbon-steel rails, head-hardened carbon-steel rails, alloy rails, and some head-hardened low-alloy rails. The improvement in wear resistance has resulted, in varying degrees, in a reduction of fracture toughness.

A modification of the residual stresses from tensile to compressive occurs in and below the in-service rail running surface by the work-hardening action of traffic; thus, in practical use, the reduction of fracture toughness in the upper part of the premium rail head is of least significance. The fracture toughness of the center and lower part of the rail head, web, and flanges are therefore more important. Hence it is suggested that the hardness and fracture toughness of these latter zones of the rail cross section will require more attention in the future.

Thus, one can visualize future interest being concentrated in the development of a rail that has web, flange, and lower head areas of tensile strength, fracture toughness, and weldability that approximates the standard AREA carbon rail but with upper head areas of increased wear resistance, albeit lower fracture toughness. The low fatigue and yield strengths that are associated with the intermediate head zones of some head-hardened rails must be avoided, since ultimately the wearing of the hardened top zone exposes these intermediate structures to contact stresses and limits total rail life. Although none of the current high-strength premium rails meet these requirements, BSC Track Products is actively pursuing this objective and limited production batches of special rails are currently undergoing service trials with a number of railroads.

Geometric Factors

The extensive amount of laboratory and in-track research work carried out throughout the world confirms the importance of geometric factors, which include track geometry and alignment, wheel and rail contact area profiles, and bogie design. The rail requirements of the future that are likely to contribute to the achievement and control of track geometry and alignment include the following:

1. Accurate cross-section dimensional control;
2. Limited surface decarburization, which may be of importance in rail head crown radius control

(alternatively, grinding or machining of head crowns may be necessary);

3. Accurate general-line and rail-end straightness;

4. Ability to weld rails to continuously welded lengths with minimum variation in the hardness and metallurgical structure in the heat-affected zone and good weld geometry alignment;

5. Control of longitudinal flatness of rail head crown (limitation of long wavelength undulations); and

6. Production of longer standard rail lengths.

However, the potential benefits of such higher standards of metallurgical and geometric properties for future rails may be dissipated without major improvement in track and traffic maintenance conditions. It is suggested that much more attention to track alignment and track geometry and to the maintenance of rail head and wheel-tire profiles is essential. The high frequency of wheel flats observed on American trains and freight cars is alarming and must be a major cause of rapid track deterioration and rail failure. It is BSC's view that these aspects must receive equal, if not more, attention in the future to those suggested aspects that relate to rail metallurgy and geometry.

U.S. MARKET-ENVIRONMENT RELATION TO RAIL TECHNOLOGY

As a foreign rail maker, my comments on the U.S. market environment may suffer from a lack of detailed knowledge and experience, but they may have some advantage in being the opinion of an outsider, viewing the scene from afar.

The most notable feature of the U.S. rail market is its size--around 1 million tons, which is 8 to 10 times the scale of the British home market for rails, which is set at about 100 000-120 000 tons/year. A second feature is that U.S. rail demands are concentrated on a few major sections and, until recently, only one family of steel grade and chemical composition was specified.

The factors of market size, a relatively few standard sections, and single rail-steel grade should encourage U.S. rail makers to specialize in rail technology and manufacture and in servicing their home market. Likewise, the rails appear to be ordered mainly to AREA specifications (or others based on them), which should simplify the manufacturers' quality control and inspection procedures. A further example of the advantage of standardization in manufacturing control is that until recently a standard length of 39 ft was used, and currently there appears to be only two standard lengths, namely, 39 and 78 ft.

Although such a large market, combined with a high degree of product standardization, may assist in reducing manufacturing costs, it appears to an outsider that the U.S. railroads have become accustomed to low rail prices to an extent that it inhibits rail-manufacturing development. U.S. track and traffic conditions are extremely severe by international standards; thus, one would expect rails of the highest metallurgical quality to be demanded by the user, albeit at a marginally higher price. In metallurgical terms, this has not been the case.

I am amazed to find that a high proportion of rails are still manufactured by what Europeans consider to be obsolete steelmaking and casting processes, namely the semikilled, or aluminum capped, open-topped-ingot practice. The potential piping, segregation, inclusions, and surface defects associated with this practice must inevitably contribute to service problems.

The following facts that relate to the U.K. rail market and manufacturing environment may be of interest. They are provided for comparison with the position in the United States to show what effect a limited home and varied export market and foreign competition can have on product quality and manufacturing standards.

The BSC Track Products' Workington Works has a rail and associated track products capacity of 250 000-330 000 tons/year. The British home market averages 100 000-120 000 tons/year. Thus, between 150 000 and 210 000 tons/year of rail are exported to a wide variety of railroads throughout the world. This involves a large number of rail sections (say, 50), a range of chemical compositions, standard rail lengths that vary from 12 to 60 ft (and ultimately to 120 ft), the use of imperial and metric dimensions and tolerances, and a variety of rail specifications and customer requirements. Frequently, this export rail order load consists of a number of small contracts for 2000-5000 tons each of a rail section of special quality and specification. In meeting customer requirements and providing the required technical and commercial services, special attention and control are necessary.

In order to meet these varied customer requirements and be capable of meeting foreseeable future demands, the more significant policies (some mentioned previously) that have been adopted by BSC Track Products include the following:

1. All rails roller straightened since 1946;
2. Higher tensile rails produced as fully killed ingots since the 1950s;
3. Semikilled rail-ingot production ceased in 1974 and thereafter the majority of rails were produced from BOF and CC blooms, with marked quality improvement;
4. Rail production gradually rationalized at fewer works and, since 1970, the policy has been to concentrate production at Workington Works, a single product mill well-suited to specialize in rail and track products manufacture;
5. The evolution of a comprehensive QA system;
6. The ultrasonic inspection of all rails for quality control purposes, and the development of BSC's own type of automatic in-line ultrasonic test equipment specially designed for rail testing; and
7. The maintenance of efficient technical and research departments that specialize in rail technology.

BSC Track Products has, in recent years, entered the U.S. market to a very limited degree, but the experience gained has given it some appreciation of the market environment. Despite earlier comments about the high degree of standardization of rail requirements, BSC appreciates that there are considerable differences between American and British markets.

In Great Britain and most of BSC's export markets, BSC negotiates generally with a single state railroad authority that generally owns or controls its own traffic, whereas in the United States there is a multiplicity of railroad companies, any of which may be handling freight cars owned by, or which have originated from, other railroads or private owners. Standards of track and traffic maintenance appear to vary considerably.

One technical difference that BSC found by bitter experience was that in the U.K. it generally produces a rail flange base that, in accordance with BS11, is either flat or concave, whereas generally American-produced rails average a slightly convex rail base. This marginal difference in profile is of great significance in the environment of American

high axle loads, generally inferior track conditions, and severe traffic conditions and led initially to some rail flange failures. Having learned from this experience, BSC now produces rails for U.S. markets in the flat or slightly convex rail base condition. This experience has also demonstrated that the long periods of heavy axle load and heavy unit train operations on U.S. railroads has resulted in a track memory being imprinted on the subgrade of many U.S. railroads, and this is likely to continue to cause many future track maintenance problems that demand considerable continuing maintenance-of-way expenditure and the best possible rail quality consistent with economic operation.

Although the pressure of some home and international markets and intense supplier competition have resulted in BSC Track Products, and indeed most European rail producers, adopting modern manufacturing process routes to improve rail quality for the more sophisticated markets, it is found to be more economic and practical to apply the improved procedures to the entire rail production, thus benefiting all customers and establishing routine standard manufacturing procedures.

CONCLUSIONS

The increased international consciousness of the need to conserve high-cost energy use has led to a resurgence of awareness of the important role of rail transport and railroads. This, in turn, has renewed worldwide interest in rail technology and the need to upgrade railroads to meet current and predicted future traffic demands. The need for

better track standards is resulting in increased pressure on suppliers for higher-quality rails.

I believe that the complete rail manufacturing process route and the individual supplier's experience in and commitment to high-quality rail manufacture are the major factors that determine its ability to meet current and future predicted rail quality requirements. It is claimed that the development and adoption by BSC of CC rail steel, the long experience and specialization of BSC Track Products' Workington Works in rail manufacture, Workington Works' routine production of rails to tighter specifications than those of AREA, plus the ongoing rail finishing plant reconstruction, enable BSC Workington Works to meet current AREA rail specification requirements and to be relatively confident of its ability to meet predicted future specifications.

However, it must be emphasized that rails are hot-rolled products of complex shape, which are required in increasingly greater length of high straightness standard. There are likely to be technical manufacturing limits to the capability of manufacturers to economically meet ever-increasing stringent rail properties (metallurgical, mechanical, and geometric).

Thus, it is emphasized that there is ample scope for railroad engineers to improve track and vehicle maintenance standards in order to match and fully use the high quality of rails currently available and likely to be developed in the short-term future.

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Rail Technology and Development in Federal Republic of Germany

W. HELLER, E. KOERFER, AND H. SCHMEDDERS

In the Federal Republic of Germany, rails are made along the lines of Union Internationale des Chemins de Fer and American Railway Engineering Association specifications that are within narrow tolerances of chemical analysis, mechanical properties, and profile dimensions. To meet the stringent requirements of heavy-duty transportation, rails should present a high degree of resistance to wear, shelling, and fatigue within the wheel-affected zone, as well as a high overall resistance to fracture. It was for this reason that an as-rolled, alloyed special grade rail was developed, with its hardness and fatigue strength being definitely higher than that of standard grade. Modern steelmaking processes, which are followed by vacuum treatment, are used to make rail steel in Germany. This permits obtaining low hydrogen and oxygen contents. The absence of flakes and nonmetallic inclusions in the rails is monitored by ultrasonic testing prior to shipment.

In the Federal Republic of Germany (FRG), rails are made along the lines of Union Internationale des Chemins de Fer (UIC) and American Railway Engineering Association specifications. This paper examines German rail specifications, behavior, and manufacturing processes.

RAIL REQUIREMENTS CONTAINED IN AREA AND UIC SPECIFICATIONS

Chemical Analysis

The AREA specifications mention one standard grade only, with its chemical composition varying slightly with the nominal weight of the rail (in pounds per yard) (1). The UIC specifications list three rail grades: one grade with 690 MPa (100 000 psi) minimum tensile strength (grade 70) and two grades with 880 MPa (128 000 psi) minimum tensile strength (grades 90A and 90B). Grades 90A and 90B, which present identical strength, differ from each other in their chemical analysis (2). Compared with grade 90A, grade 90B presents a higher percentage of manganese and a lower percentage of carbon. As far as their service behavior is concerned, we feel there is no difference between grade 90A and grade 90B. Grade 90A is comparable to rails made in accordance with AREA specifications.

The table below shows a comparison between the specified AREA and the grade 90A analyses: