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.

Publication of this paper sponsored by Committee on Track Structure System Design.

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:

Rail Grade	Alloying Elements (%) C	Mn	Si
Area (>121 lb/yard)	0.69-0.82	0.75-1.05	0.10-0.35
UIC 90A	0.60-0.80	0.80-1.30	0.10-0.50
UIC 90A [section UIC 60 (120 lb/yard)]	0.70-0.78	0.92-1.12	0.22-0.29

It can be seen from these analyses that UIC allows wider analysis margins than AREA. However, it must be taken into consideration that the UIC analysis encompasses the entire field of rail profiles. It is up to the manufacturer to narrow down the analysis for each of the profiles on the basis of their specific manufacturing conditions and the necessary mechanical properties. Line 3 of the above table represents the analysis narrowed down for the UIC 60 rail profile. A comparison of the analysis margins reveals that only half of the UIC margin was used for making this grade and that the margin was also definitely reduced with respect to the AREA analysis.

Figure 1. Mechanical properties of rail steels [sampling 17 mm (0.66 in) below surface].

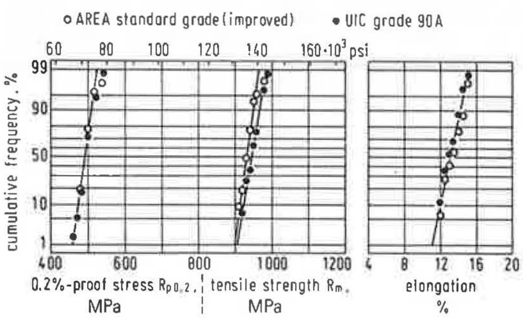


Figure 2. Brinell hardness and tensile strength of rail steels.

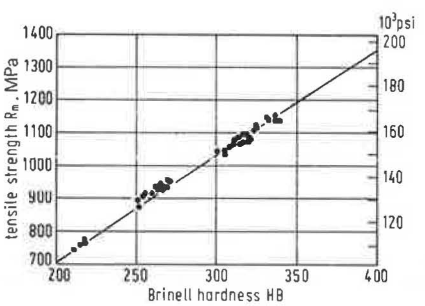
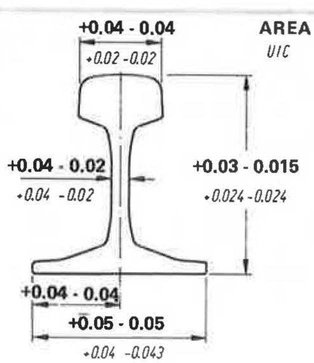


Figure 3. Dimension tolerances (in inches).



Mechanical Properties

Although AREA specifications specify only Brinell hardness (HB), UIC specifications call for distinct mechanical properties. For shipment to the United States, we have produced rails that we feel represent an improved AREA standard grade. Instead of a Brinell hardness of 248 HB, we have observed a minimum hardness of 269 HB and, in addition, we have conducted tensile tests on samples taken from the rail head. Figure 1 shows the 0.2 percent proof stress, the tensile strength, and the elongation at fracture for the improved AREA standard grade in comparison to UIC grade 90A. The mechanical properties of both grades correspond almost completely. In this connection, note that, at the same tensile-strength level, UIC grade 90B exhibits an elongation at fracture that is on average 1 percent higher due to its lower carbon content. However, this does not in any way influence the service properties.

Tensile strength and hardness of rails show a very good linear relation, as demonstrated in Figure 2. Thus, for UIC rail, the minimum tensile strength of 880 MPa corresponds to a hardness of 260 HB.

Tolerances

Figure 3 provides a general idea of the most important UIC and AREA cross-section tolerances. It can be seen from this figure that the tolerances are practically identical for rail height and rail web thickness. For the width of the rail head and base, UIC specifies a more narrow tolerance than AREA.

The straightness requirements for rail ends are nearly identical to each other. According to UIC, the entire length of the rail must be straight on visual inspection. However, some railway administrations go far beyond this requirement. Thus, the German Federal Railways specifies a straightness deviation of 0.3 mm (0.012 in) for approximately 2 m (2.2 yards) in length, with a fraction of 5 percent being allowed to present a deviation of 0.3-0.4 mm (0.012-0.016 in). Such requirements can be met only by means of roller straightening. In this respect, particular importance is being attached to the adjustment of the roller straightener.

The narrow straightness tolerances are caused by the high speeds of passenger trains. Since roller straightening confers internal stresses on the rail, the question is whether or not the straightness requirements can be relaxed for low-speed freight trains in order to obtain less internal stresses by milder roller straightening.

In summary, it can be stated that the properties required by AREA and UIC can be complied with by German rail producers without any difficulties.

SERVICE BEHAVIOR

To withstand high loads that frequently occur in heavy-duty transportation, rails should exhibit a high degree of resistance to wear, plastic deformation, and fatigue damage within the wheel-affected zone. In addition, they are expected to have a high resistance to fracture.

Resistance to Wear

Wear resistance of a rail is governed by its microstructure and tensile strength (or hardness). All rails under review present a pearlitic structure so that only their tensile strength or hardness is of importance for the assessment of their wear behavior.

For example, by using measurements made on high rails in the curved tracks of Deutsche Bundesbahn (DB), Schweizerische Bundesbahnen (SBB), and Rhein-

Figure 4. Wear in high rails of pearlitic steels with different tensile strength.

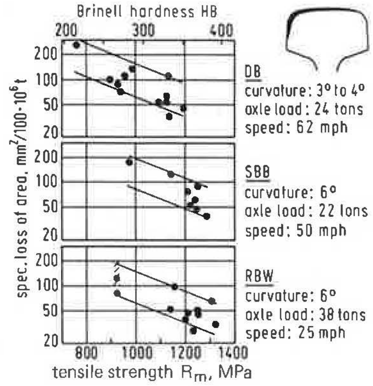


Figure 5. Mechanical properties of rail steels for the United States [sampling 17 mm (0.66 in) below surface].

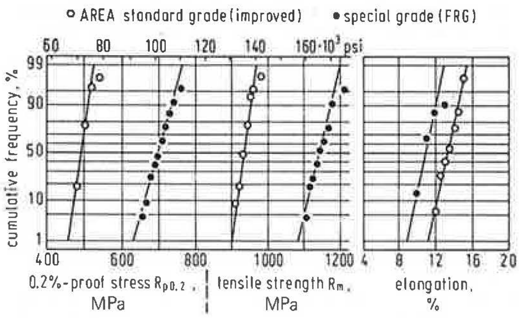
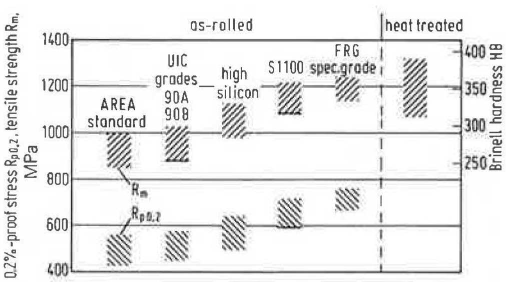


Figure 6. Standard, alloyed, and heat-treated rail steels [sampling 10 mm (0.39 in) below surface].



ische Braunkohlenwerke (RBW) (with a 38-ton axle load), Figure 4 demonstrates that wear diminishes by roughly 50 percent if the tensile strength increases by 200 MPa (30 000 psi) and the hardness by 65 HB, respectively (3). By increasing the tensile strength and by using suitable lubrication, wear remains low, even in narrow curves. Related to the overall load, loss of area can be kept below 100 mm² (0.15 in²) per 100 million tons. Since such a loss of area corresponds to 2 mm (0.08 in) in lateral wear, more than 500 million tons in overall load are attainable by high-strength steels.

Tensile Strength

Based on the experience gained from rails that operate under high loads (4), German mills developed for the U.S. market an improved, as-rolled, alloyed special grade that presents a definite increase in yield strength, tensile strength, and fatigue strength over the standard grade (5). Figure 5 illustrates the mechanical properties of this grade against those of the improved AREA standard grade.

Compared with the improved AREA standard grade, 0.2 percent proof stress and tensile strength of the special grade are increased by approximately 200 MPa. This increase in strength is accompanied by an improvement in fatigue strength and thus by an improvement in the resistance to fatigue damage. Related to service behavior, this means the rails should remain exempt from plastic deformation of the rail head and from fatigue damage. In addition, service life should increase two to three times through reduced wear.

In Figure 6, this special grade is once again compared with as-rolled standard and other special grades and with heat-treated rails. Within the framework of as-rolled grades, the FRG special grade represents the latest development. The comparatively narrow scatter band of its tensile strength coincides with the mean tensile strength of heat-treated rails and anticipates comparable service behavior.

In addition, for resistance to fatigue damage in the rail head, a high degree of cleanness with respect to nonmetallic inclusions is of crucial importance (6). As shown in the next section, cleanness is obtained through modern production processes and sensitive ultrasonic testing prior to shipment. The lower the rail wear, the more important high resistance to fatigue damage is because the stress maximum in the rail head due to the wheel effect strains the same volume of material more frequently.

Resistance to Fracture

The fracture-mechanics concept is a useful assessment of the rail's resistance to fracture since the rail-steel properties (as demonstrated by recent investigations) can be used quantitatively to determine the fracture behavior of the rail as a construction element (7). The critical depth of a rail surface crack that tends to produce a brittle fracture right across the entire rail can be calculated if the fracture toughness and the effective stresses of the rail steel are known.

In pearlitic rail steels, the fracture toughness remains constant within a wide scatter band, in spite of increasing tensile strength, as shown in Figure 7, which summarizes the results contained in several papers (8). It ranges from 1000 to 2000 $MPa^{3/2}$. In this respect, even maximum-strength rails with good wear resistance are accompanied by a high resistance to fracture.

MANUFACTURING PROCESSES (NONMETALLICS)

Steelmaking

In the FRG, rails are manufactured along the lines of the basic-oxygen-furnace (BOF) and, in part, the open-hearth (OH) processes. In all cases, steelmaking is followed by vacuum treatment (9,10). In Germany, the usual vacuum treatment is aimed mainly at the removal of hydrogen from the steel. Figure 8 illustrates the frequency distribution of hydrogen content in OH and BOF steels, with and without vacuum treatment. Hydrogen distribution in OH steel with no vacuum treatment presents such contents in all heats so as to require retarded cooling. Standard BOF heats have hydrogen percentages that require retarded cooling only for about 50 percent of the heats. Regardless of the initial hydrogen content, vacuum treatment ensures obtaining such low-hydrogen contents that, even in cases of normal, unretarded cooling, a sufficiently large safety margin is provided in relation to critical contents

Figure 7. Fracture toughness and tensile strength of rail steels.

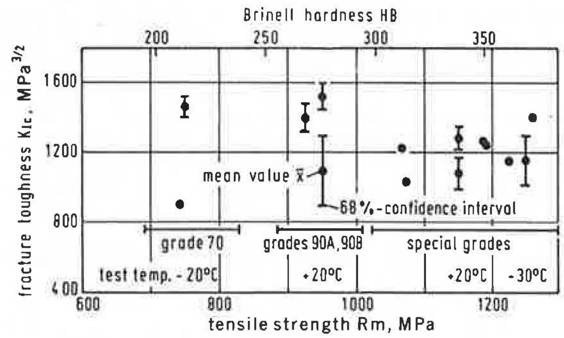
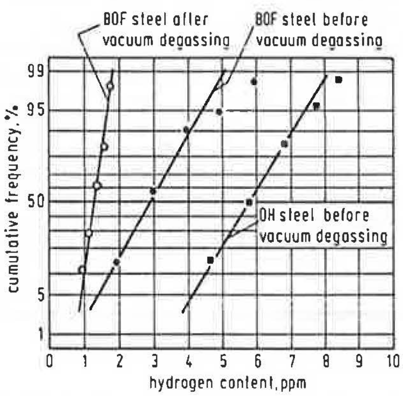


Figure 8. Frequency distribution of hydrogen contents in BOF and OH rail steels.



that tend to cause flake formation (11). This allows the rails to be cooled on the cooling bed without taking any particular precautions. It brings the full effect of the chemical analysis to bear on the strength properties. Besides, unretarded cooling is a prerequisite for a rational production flow, in particular for the manufacture of rails up to 60 m (65.2 yards) in length.

Combined with suitable deoxidation, vacuum treatment also leads to oxygen contents as low as 0.0025-0.005 percent. This means that only minor percentages of oxidic, nonmetallic inclusions are still present in the finished rail.

Pouring

Rail steel is either strand-cast or poured in hot-top molds (12). Both methods ensure good surface conditions that are important for rails. The use of hot-top molds leads to a steel with reduced segregation; the antipiping powder keeps the ingot top in a liquid state until complete solidification so as to prevent piping within the used ingot part, thus allowing inclusions to precipitate into the hot top during solidification. The hot top is cropped after blooming. Continuous casting produces a bloom almost free from segregations. Suitable steps ensure good cleanness, with the rapid solidification of the strand-cast material also providing a fine distribution of the inclusions.

The absence of flakes and coarse nonmetallic inclusions in the rails is monitored by way of ultrasonic testing prior to shipment. So far, no damage has been observed on rails as a result of inclusions that would have been detectable through ultrasonic testing. The question as to whether or not minor inclusions below ultrasonic detection sensitivity are likely to cause fatigue damage under extreme conditions is being studied at present within the framework of a joint investigation monitored by the rail committee of Verein Deutscher Eisenhüttenleute in cooperation with DB.

The testing methods used make sure that the A-type rails are qualitatively equivalent to the standard rails made from conventional or strand-cast ingots. We feel that, when using these methods in combination with continuous ultrasonic testing, the nick-and-break test required in AREA specifications can be dispensed with.

MARKET ENVIRONMENT

We feel that the German rail producers are capable of fully meeting the rail requirements of the U.S. market. Compliance with close tolerances is possible as a result of stable and partially prestressed rolling stands. Roller straightening ensures a high degree of straightness.

For normal operating conditions, the improved AREA standard grade can be supplied. For operating conditions with more stringent requirements, such as heavy-duty transportation that uses 100- to 125-ton cars and, in particular, on railway lines with many curves and a great number of trains, an as-rolled, alloyed special grade is supplied that is identical in its service behavior to heat-treated rails. The fracture toughness of the standard grade is obtained in spite of the great tensile strength, so that sufficient resistance to fracture is also warranted.

Appropriate steelmaking and casting processes lead to obtaining low hydrogen and oxygen contents. This ensures the absence of shatter cracks and coarse nonmetallic inclusions. It is the high degree of cleanness with respect to nonmetallic inclusions that, combined with the enhanced fatigue strength, confers a high degree of resistance to fatigue damage on the alloyed special grade.

REFERENCES

1. Specification for Steel Rails. American Railway Engineering Association, Washington, DC, 1979.
2. Technische Lieferbedingungen für Schienen. Internationaler Eisenbahnverband, UIC-Kodex 860, Vol. 7, Jan. 1, 1979.
3. W. Heller, R. Schweitzer, and L. Weber. Conference on Modern Developments in Rail Steel Metallurgy and Production, Halifax, Canada, Aug. 1980.
4. W. Heller, E. Koerfer, and H. Schmedders. Naturally Hard Special-Grade Rails for Heavy-Duty Transportation. Presented at Heavy-Haul Railways Conference, Perth, Australia, Sept. 1978.
5. H. Schmedders. A Chromium-Vanadium Alloyed Rail Steel for Heavy-Duty Requirement: Vanadium in Rail Steels. Proc., Vanitec Seminar, Chicago, Nov. 1979.
6. W. Heller and R. Schweitzer. Untersuchungen zum Betriebsverhalten von Schienenstahl. Archiv für Eisenbahntechnik, Vol. 28, 1973, pp. 81-89.
7. R. Schweitzer and W. Heller. Rißzähigkeit, Eigenspannungen und Bruchsicherheit von Schienen. Tech. Mitt. Krupp, Werksberichte Band, Vol. 39, 1981, pp. 33-41.
8. J. Flügge, W. Heller, and R. Schweitzer. Gefüge und mechanische Eigenschaften von Schienenstählen. Stahl und Eisen, Vol. 99, 1979, pp. 841-845.
9. R. Hammer, D. Phlipsen, H. Schmedders, and J. Trenkler. Erzeugung von verschleißfestem Schienenstahl nach dem Sauerstoffblasstahlverfahren mit nachfolgender Vakuumbehandlung des flüssigen Stahles. Eisenbahntechn. Rdsch., Vol. 23, 1974, pp. 463-468.

10. H.-M. Delhey, L. Fiege, and H. Vorwerk. Konzeption und Einsatz der DH-Vakuumanlage im LD-Stahlwerk der Fried. Krupp Hüttenwerke AG, Werk Rheinhausen, Stahl und Eisen, Vol. 99, 1979, pp. 18-23.
11. W. Heller, L. Weber, P. Hammerschmid, and R. Schweitzer. Zur Wirkung von Wasserstoff in Schienenstahl und Möglichkeiten einer wasserstoffarmen Erschmelzung. Stahl und Eisen, Vol. 92, 1972, pp. 934-945.
12. H. Schmedders and F. Weber. Manufacture, Testing, and Properties of 60-Meter Rails from Strand-Cast Material. Thyssen Technische Berichte, Heft, Feb. 1980.

Publication of this paper sponsored by Committee on Track Structure System Design.

Analytical Descriptions of Track-Geometry Variations

A. HAMID AND T-L. YANG

Track-geometry variations can be divided into two broad categories: (a) typical variations that account for random waviness in the rail and periodic behavior at joints, and (b) isolated variations that occur occasionally but do have regular patterns. An overview of analytical descriptions of track-geometry variations found in U.S. track is given. These descriptions provide mathematical representations required for simulations and design studies. Time-series-analysis techniques were applied to develop the statistical descriptions of typical track-geometry variations. Models based on autospectral densities are presented along with the parameters of these models for the current Federal Railroad Administration track classes. Various shapes of isolated variations as found in U.S. track are identified. Mathematical functions for these shapes are given along with the values of parameters of these functions. Also discussed are the relations between track-geometry parameters. This includes correlations between gage and alignment, cross level and alignment, and cross level and profile.

Track-geometry variations are the primary dynamic inputs to rail vehicles. In order to study vehicle-track interaction, it is essential to provide quantitative descriptions of track-geometry variations. Analytical descriptions of track-geometry variations are essential in performing simulation studies for improved rail safety. Such descriptions are also needed for evaluation of track quality, vehicle performance, passenger comfort, and lading damage. Since an infinite number of track-geometry variations can occur in the railway track, a statistical approach is used in the characterization of track-geometry variations.

Track irregularities or variations in track geometry are the result of cumulative forces that have shaped the track structure during its lifetime. These variations often begin with small imperfections in materials and tolerances and errors in the manufacture of rail and other track components. Terrain variations and survey errors during the design and construction of track also add to the variations. Progressive deterioration of track geometry occurs under traffic and environmental factors. Various deformations may sometimes be induced by maintenance operation intended to correct poor geometry.

Most track can be separated into segments that are constructed and maintained in a uniform manner. These segments exhibit similar track-geometry variations that consist of random waviness with relatively large amplitudes at joints and welds. Such variations are called "typical" variations in this paper.

Track-geometry variations not covered by typical variations will be called "isolated" track-geometry variations. Isolated variations usually occur at special track work or at physical features such as switches, turnouts, crossings, and bridges. These variations occur occasionally, but they do have regular patterns.

A track-geometry data base that represents a reasonable sample of track in the United States was established for the analytical characterization of track-geometry variations. The data base consists of approximately 500 miles of track-geometry data selected from approximately 70 000 miles of data collected by Federal Railroad Administration (FRA) track-geometry cars during 1980 and 1981. The data base consists of 5-10 sections of track-geometry data in each of the current FRA track classes (FRA, Track Safety Standards, 1973). Each section varied from 5 to 10 miles in length. These sections were broadly distributed throughout the United States and reflected various types of operating conditions and maintenance practices of different railroads.

Analytical descriptions of track-geometry variations were developed under a track characterization program directed by the Transportation Systems Center in support of the FRA improved track structures program. This program was initiated in 1976 and two interim reports have been published (1,2). This paper gives an overview of the results of this program.

TYPICAL TRACK-GEOMETRY VARIATIONS

Time-series-analysis techniques (3) were applied to track-geometry data to obtain analytical representations of typical track-geometry variations. It was shown that a periodically modulated random process provided an adequate representation of typical track-geometry variations (4). This process consists of a stationary random process that accounts for the random irregularities in the rail and a periodic process that describes the regularly spaced rail joints that have a non-zero mean amplitude. The amplitude of joints varies randomly while the joint spacing stays the same.

The power spectral density (PSD) is a useful tool for analyzing the periodically modulated random process. In track-geometry PSDs, the stationary random process produces the smooth continuum and a non-zero mean in joint amplitudes (periodic process) causes spectral peaks.

Figure 1 shows a typical PSD of the profile geometry of bolted track. The power density is plotted as a function of spatial frequency (1/wave-