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“Rail-Corrugation and its Causes.”

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SINCE the introduction of electricity as a motive power for traction purposes, the corrugation of rails has seriously exercised the minds of owners of electric tramways and railways. Corrugation on cable- and steam-tramway lines was familiar to engineers before the introduction of electric traction, but it had not, under those conditions, become the serious menace to these undertakings which it is to-day.

Within the limits of a short Paper it is not possible to give a detailed résumé of the researches which have been published and are accessible to all who are interested in the subject; nor does it seem to be necessary or advisable to comment on or criticize the various reports which have been made, or the theories which have been advanced to account for rail-corrugation. The Appendix to this Paper contains some references to published articles of especial importance dealing with the subject. The Author's object is to submit to The Institution the present position of tramway undertakings, as affected by the phenomenon in question, in the hope that some general discussion of the matter may assist towards finding a remedy for a grave engineering difficulty, which has so far baffled all researches.

A considerable number of tramway undertakings are to-day expending large sums of money on the process of grinding-out corrugations, incidentally reducing in a considerable degree the useful life of the rails, and thus continuously wasting their capital as they destroy their material. This is a serious burden on these undertakings, demanding earlier renewal of the rails, which in its turn involves complete displacement and replacement of extensive areas of street surface. The Author trusts that his attempts to

secure attention to and interest in this matter will not be regarded as due to exaggeration. To give an example, it has been estimated by the chief officer of the City of Glasgow tramways that rail-corrugation cost that undertaking at least £10,000 per annum.¹

The Author's own experience, supported by most authorities who have given close attention to this question, is that the steel rail of to-day is neither hard enough nor tough enough to meet the duty imposed upon it by the present conditions of electric traction. To these views may be added some very influential opinions that the modern methods of manufacture, involving the use of large ingots, rapid rolling at high temperatures, and consequent absence of homogeneity, are considerable factors in rail-corrugation.²

The Author believes that the use of wheels of comparatively small diameter is one of the causes of rail-corrugation, and in this opinion he is supported by other engineers and by certain ascertained facts; but the difficulty of increasing wheel-diameters on street-cars is so great that he thinks such a course must be set aside as impracticable. It therefore becomes necessary to find a rail-material which will not yield to the wheel-actions which are the immediate cause of corrugations. The Author has already stated that hard rails, i.e., with a high proportion of carbon, are essential, and he finds it stated by an important continental authority that rails which contain carbon exceeding 0·55 per cent. and phosphorus less than 0·08 per cent. have never been found corrugated. The Author's personal experience is, that well-made rails containing a high percentage of carbon are practically free from trouble. Further, there is recent evidence³ that a high proportion of silicon added to the rail-steel gives a satisfactory increase of life by its greater resistance to corrugation, as well as to ordinary wear. In leaving this portion of the subject, the Author would observe that between 1898 and 1903 he was responsible for the purchase of 10,000 tons of tramway-rails, to a specification which included a high proportion of carbon, namely, not less than 0·60 per cent. The terms of the specification were strictly enforced during inspection, and the rails were laid in various English towns. On those rails no corrugation has occurred; whereas, when the tramway systems referred to have been extended with rails containing between 0·40 and 0·55 per cent. of carbon,

¹ Mr. Dalrymple. *Tramways and Light Railways Association Circular*, August, 1908, p. 764.

² Mr. Busse. *Ibid.*, October, 1910, p. 1249.

³ *Light Railways and Tramways Journal*, 11 June, 1909, "District and London Electric Railways."

corrugation has appeared on these extensions, although the method of construction and the rolling stock carried by them are the same. With such experience it is difficult to come to any other decision than that, while there are many causes tending to produce corrugation, it is the character of the rail in resisting that phenomenon which is the chief practical factor, and the one which should be dealt with. The trouble known as corrugation, or "roaring rails," is an undulatory deformation or wear of the rail-table, the surface being alternately raised or depressed at fairly regular intervals. Vehicles running on such corrugated rails produce a characteristic noise, aptly described as "roaring." The corrugations are generally visible from an early stage of their development, the high parts appearing bright, as if planished or "cold rolled," and the low parts relatively dull, somewhat like acid-dipped steel. The high bright patches are also harder than the low dull patches. There is generally some lateral spreading or detrusion of the surface metal, which forms a lip or cornice slightly overlapping the rail-table—sometimes only at the hollows, but sometimes continuously. The pitch or interval between successive crests is generally between 2 and 3 inches, but reaches extremes of about 1 inch and 6 inches; it is fairly regular over lengths covering a few crests, but may change considerably in the course of a continuous length of corrugation. It is at times irregular, as though two or more pitch-lengths were superposed. So far as measurements are available, the height of the waves, crest to hollow, does not exceed $\frac{1}{100}$ inch. These dimensions apply particularly to tramways. Corrugation usually appears in patches separated by lengths of uncorrugated rail, the patches tend to extend lengthwise, but it rarely or never happens that the whole of a tramway line becomes corrugated. At any given place only one rail of a track may be corrugated. A length of corrugation will sometimes disappear, without special treatment, but this is unusual. It is more common for the pitch to change gradually.

Corrugation affects straight track and curved track. There seems to be a small consensus of opinion that it is most prevalent on curves of relatively long radius, and is rarely seen on curves of such short radii that considerable grinding wear occurs. There is sometimes, however, visible indication that the corrugating influence operates on short-radius curves, but its effects are almost entirely masked by grinding wear.

The foregoing description covers most of what can be described positively as a general characterization of the evil. Many individual cases could be cited to show that corrugation occurs, or does not

occur, under given conditions; but every such instance would be confronted by a direct negative from some other case. The result is, that whilst much study has been directed to the endeavour to elucidate the cause and prescribe a remedy, every investigator has so far found himself baffled by the fact that so soon as he leaves a particular case and examines another, he finds his previous conclusions as to the causes of the evil contradicted.

The Author is not in a position to generalize as to the causes of corrugation so as to reconcile all the available evidence, or to pronounce for or against any of the theories heretofore advanced, but it seems possible that a remedy is available, and it is to this point that he would direct attention. It will be agreed by every one that corrugation is an effect produced on the rails by the action of the car-wheels which run on them. It will also be agreed that corrugation has become a general and serious evil only since electric traction has become common on tramways. It has occurred somewhat severely on cable tramways, but in the Author's experience it has not been extensive on steam tramways.

The general introduction of electric traction about 15 years ago changed simultaneously several conditions affecting the actions between wheels and rails, and coincided with a considerable change in the character of the rails themselves. Owing to the great demand which then sprang up, the number of rail-makers increased, and their efforts naturally were directed towards the development of processes of steel- and rail-making suitable to the economical output of large quantities of rails in the minimum of time. Rails of the heavy sections then called for were comparatively new, being 40 to 50 per cent. heavier than railway rails and of considerably different section. Up to the date at which the current British Standard specifications for tramway rails were issued, the danger of corrugation had not been realized, and nobody at that time thought particularly of preventing it by insisting on any particular feature or quality in the rails, or in the material of which they were to be made.

The nature of the wheel-action on the rails is one question, and the manner in which such wheel-action is set up forms another question, upon which the Author does not now propose to touch. Evidence of the nature of the wheel-action is furnished by the rail affected, and no theory or explanation of the subject can be correct which is inconsistent with that evidence.

The effect of the smooth uniform rolling of a loaded wheel upon a rail is to polish and make smooth the surface of the rail-table, imparting a superficial hardening exactly as in the cold-rolling process used for finishing steel sheets. In addition to this cold-rolling

effect, there is always more or less abrasion due either to slip or skid of the wheel and to its lateral movement, i.e., to relative movement between the contact areas of the wheel-tread and the rail-table, producing some grinding, which is evidenced by the bright metallic surface. Hence the effect of smooth running of a loaded wheel upon a rail is a combination of cold-rolling and grinding. This is the appearance presented by the crests of a corrugated rail. The hollows are, however, dull in colour and when carefully examined they show surface pitting, and, in general, some lateral detrusion, generally towards the groove side, but at times also towards the outside. The dull surface proves at once that the hollows are not produced by the grinding of the wheel, since in that case they would be bright; the lateral detrusion proves that the compressive elastic limit of the steel has been exceeded, and that the metal has flowed on its free edges. The pitted appearance of the surface shows that metal has been displaced otherwise than by grinding, and it is not accounted for by the cold flowing. Therefore it can only have been displaced by local crushing. Thus, the evidence given by the rail is, that in the hollows it has been subjected to a load in excess of its elastic limit, producing the two effects of surface crushing and flow of metal. On the crests rolling and slight grinding have prevailed, without surface destruction.

Tests of hardness confirm these conclusions, the rail-table being harder at the crests than at the hollows, and the hardness of the hollows somewhat greater than that of the body of the rail, which would appear to suggest that the destructive pressure in the hollows crushes the surface but hardens the material immediately below—as might be expected. Etching with acid attacks the hollows more than the crests, and frequently indicates the detrusive action by showing outward curving of the striation of the steel.

From this evidence it seems clear that corrugation is set up by an intermittent variation of wheel-pressure, something in the nature of a vertical vibration in load-intensity, which reaches a destructive amount at the hollows, and falls below destructive intensity at the crests. How the vibration is set up, why it persists, and why successive vehicles fall into step over the corrugated lengths, are questions involving complicated reactions as between the wheel and the rail, and between the wheel and the rest of the vehicle, which the Author does not propose to examine. They have formed the subject of prolonged discussion, marked by great diversity of opinion and conflict of evidence, which has so far led neither to a generally accepted conclusion or theory, nor to a practical remedy for the evil.

Motor-vehicles are found to "corrugate" macadam roads, different vehicles appearing to fall into step, and so far presenting some analogy to the corrugation of rails by cars; but the pitch of these road corrugations is clearly related to the "pitching" period of the vehicle as a whole, whereas the pitch of corrugated rails corresponds with a vibration frequency of the order of 100 per second, i.e., either to a very short radius of gyration, or to a very powerful control force, or to both combined.

Returning to the rail, it has been suggested that in the process of manufacture a rail may receive initial corrugations which will develop under traffic. There is evidence that some new rails have been found to be slightly corrugated; but an examination of 30,000 tons of new rails on behalf of the Special Committee of the Municipal Tramways Association on Rail Corrugation (Interim Report, August, 1912) revealed no indications of corrugation, so that such initial defect is apparently exceptional. It is, however, possible that without production of a wavy surface there may be a periodical variation of hardness in the rail-table, due to chattering of the rails set up by the gearing. For example, the table of the rail does not receive direct pressure from the cylindrical parts of the rolls; such direct pressure bears upon the sides of the rail-head, and the metal is forced up to the roll surface forming the table by lateral flow. It is therefore conceivable that chattering of the rolls may cause a variation of the pressure, and therefore of the density or resulting hardness of the metal forming the table. Such an effect, however, if at all large, would seem likely to produce marks on the side faces which receive the roll pressure directly. It seems possible that a rail undergoing its finishing passes near a "recalcescence" point of the steel might have its ultimate hardness affected by comparatively small differences of roll-pressure, if such differences forced the temperature alternately above and below the critical point.

Another process in which variation may be set up is that of cooling after rolling. A rail laid out by itself, i.e., not in a heap with others, will evidently cool most rapidly in the flange, next at the base of the web, and most slowly in the head. The differential contraction will make it convex on the head at first, and later the contraction of the head has to straighten the stiff flange and web which are already relatively cool. The guard side of the head also cools more rapidly than the table side, which tends to produce lateral curvature. These effects, and those produced by the straightening rolls, are certain to set up internal stresses which will be most pronounced in the part which remains plastic over the

longest period, namely, the head, and it seems possible that they may leave a condition of varying hardness, or of tendency to deformation, which yields to the wheel-action, in varying degree, and so lends itself to corrugation. The effect is more than skin deep. On the London County Council tramways corrugations are "rubbed out" as soon as they become sufficiently serious, and the rubbing-out has been repeated several times over certain lengths of line. The corrugations reappear after various intervals; sometimes they become quite deep within 3 or 4 months. In a few cases the number and pitch of successive crops has been observed, and it is found that they may be widely different. So far as it goes, this fact is opposed to the suggestion of internal stresses, or differences of hardness in the material, or at least it indicates that such effects vary rapidly in the vertical direction. Any such effects can be proved satisfactorily, and their causes traced, and remedied, only by research work in the rolling-mills; and it seems desirable that this work should be undertaken.

Leaving suggestions of this kind, the fact remains that corrugation is due to the failure of the rail-table under the stresses imposed upon it. The surface is alternately disintegrated and cold-rolled, suggesting that the stress passes through the critical point with a high frequency. Where corrugation is absent the stress may be constantly in excess of the elastic limit, with the result of rapid but uniform wear. Rails are sometimes seen to present very faint corrugation marks which get no deeper; but such rails are generally wearing rapidly, i.e., they are wearing by surface crushing, or, as is frequently seen on sharp curves, by grinding, in which case there may be faint corrugation marks superposed on the generally bright face which is characteristic of abrasion.

Measurement of the static pressure imposed on rails by the wheels of tramway-cars has been attempted by Mr. W. Worby Beaumont, M. Inst. C.E.,¹ who loaded the axles of a pair of driving-wheels and of a pair of pony wheels of a London County Council car ("maximum traction" truck) with weights equal to their working loads, and, measuring the areas of contact between wheel-head and rail-table, deduced pressures averaging 11·96 tons per square inch on the driving-wheels and 31·8 tons per square inch on the pony wheels. It is noticeable that the total load on the driving-wheels, which were 31 inches in diameter, was 6 tons, and that on the pony wheels, 21 $\frac{9}{16}$ inches in diameter, was 3 $\frac{1}{4}$ tons, showing the marked effect of smaller wheel-diameter in intensifying the stress.

¹ Report of the British Association for the Advancement of Science, 1911.

As Mr. Beaumont pointed out, the maximum pressure in the centre of the contact area must be higher than the average pressure. When running, impact effects, or effects of vertical oscillation, may easily bring the maximum pressure to an amount exceeding the compressive elastic limit of the steel, in which case flowing or surface crushing must occur. It is not necessary to discuss Mr. Beaumont's suggestions as to the maximum intensities which occur in running. Whilst his measurements show that these pressures may attain a magnitude of the order required to produce destructive effects, experience shows that such a magnitude is not general. If it were, all rails run over by similar cars would be destructively affected, which fortunately is not the case. It therefore appears more correct to say that the stresses attained oscillate about the elastic limit of the rail-steel in general use, and that the presence or absence of corrugation, or of uniform disintegrated wear, on rails carrying the same traffic, is due to varying hardness of the rails, resulting probably from differences of heat-treatment and working in the rolling process, or due possibly to small differences in the composition.

The evidence, therefore, seems to show that a comparatively small increase in the compressive strength of the steel will prevent the particular kind of wear under consideration. This means, of course, a harder steel. The current British Standard specification for tramway rails prescribes the proportion of carbon in the steel as 0·40 to 0·55 per cent., a rather wide range, of which the upper point only just encroaches on the hard side for steel made by the Bessemer process, whilst for open-hearth material this percentage gives a comparatively soft steel.

The cold flowing of the rail surface, detruding into the groove, or to the outside of the rail-head, is a general concomitant of corrugation, and has been noticed as a frequent precursor of this trouble.

It seems desirable, therefore, that the composition of rail-steel shall not be such as to confer a high degree of ductility. It is not the purpose of this Paper to suggest a composition specification, but it does appear that rails which conform to the British Standard specification may have too low an elastic limit, and too high a measure of ductility.

The Author wishes to suggest that the essential points to be specified are mechanical properties corresponding with the working-stresses imposed upon the rails.

The first point is compressive strength. The British Standard specification prescribes an ultimate tensile strength of not less than 40 tons per square inch; and as tensile strength and compressive

strength are generally about equal in mild steel, this may be taken as the intention of the specification in respect of compressive strength. In the face of Mr. Beaumont's measurements, 40 tons is evidently too low, and it is probable that most rails actually possess a higher strength. Probably steel with an ultimate tensile strength of 50 to 60 tons per square inch will be found hard enough to resist the destructive stresses. The Author would suggest, however, that the actual qualities required should be specified by well-known means, and should include a determination of the minimum pressure needed to produce surface crushing. Neither flowing nor crushing should occur, he considers, at less than 60 tons per square inch, although no figures should be fixed until they have been proved by experiment to be adequate.

The method of testing is also a proper subject for experiment and discussion, but it seems that a Brinell test may give all the information needed, if the impressions made are examined for both detrusion and crushing. It will be obvious that in obtaining the mechanical qualities sought for, it is necessary to avoid brittleness, and to keep the metal sufficiently tough to enable rails to be curved by the usual methods, and not too hard to drill. However, some additional cost of labour to secure more careful bending, and perhaps more expensive drills of special steel, can well be afforded if corrugation and excessive rates of wear can be avoided. It is probable that the tup test would have to be modified to suit steel with such properties as those indicated above, but rail-breakage is so rare on tramways with a continuous concrete substructure that there is evidently a large margin of safety in that respect, and a less severe tup test should suffice. In any case, the tup test represents nothing to which the rail is exposed in the course of its work, and the Author would suggest that the whole specification of the rail in respect to its mechanical qualities should bear a direct relation to the stresses which it will be called upon to resist. Given such a specification as the necessary logical basis, there can be no doubt that the steel metallurgists and manufacturers will know how to determine the chemical composition, and the processes of rolling and heat-treatment needed to produce the article needed, and will succeed in this, as they have done in so many other steel products which a few years ago seemed to be economically unattainable.

APPENDIX.

Some Papers and Reports recording the results of experiments and reasoned accounts of the phenomenon. There is also a large number of Papers of a descriptive or argumentative character.

- J. A. PANTON . . . "Rail Corrugation," Journal of the Institution of Electrical Engineers, vol. 39 (1907), p. 3.
- A. BUSSE Report to International Tramways Congress, Milan, September, 1906. Tramways and Light Railways Association Circular, June, 1907.
- A. L. C. FELL Report to London County Council. Tramways and Light Railways Association Circular, October, 1907.
- C. A. CARUS-WILSON Tramways and Light Railways Association Circulars, July and August, 1908.
- BUSSE, A. Report to International Tramways Congress, Munich. Tramways and Light Railways Association Circulars, June and July, 1909.
- W. WORBY BEAUMONT Paper, "The Origin and Production of Corrugation of Tramway Rails" (communicated to the British Association, 1911), Tramways and Light Railways Association Circular, October, 1911.
- A. SCHWARTZ and R. G. CUNLIFFE. "The Corrugation of Rails," Journal of the Institution of Electrical Engineers, vol. 49 (1912), p. 559.
- MUNICIPAL TRAMWAYS ASSOCIATION. Interim Report of Special Committee on Rail Corrugation, August, 1912.
- DISCUSSION ON ABOVE *Tramway and Railway World*, 1912, vol. 32, p. 285.
- A. BUSSE Report to German Tramways and Light Railways Association Congress, Cologne. Tramways and Light Railways Association Journal, Nov. 7 and Dec. 5, 1913.
- G. E. PELLISSIER. "A New Theory of the Cause of Rail Corrugation." *Electric Railway Journal* (New York), vol. 38 (1911), p. 528.