THE WEAR OF BAINITIC AND PEARLITIC STEELS

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ABSTRACT

The rolling-sliding dry-wear behaviour of a series of bainitic steels and a standard pearlitic rail steel have been compared over a range of contact stress and creepage conditions applicable to the British Rail network. A rolling-sliding wear machine has been constructed - LEROS - which allows very high contact stresses to be combined with high creepages under well controlled conditions. Materials were tested on LEROS and on an Amsler machine. Limited vibration analyses were carried out on both machines and compared with the frequencies of disc surface periodic undulations. No direct linkage was determined.

Despite better standard mechanical properties, the wear resistance of lower carbon bainitic steels was inferior to that of the pearlitic steel. A bainitic steel with the same carbon content as the pearlitic steel wore a little less, but at considerable expense to the pearlitic wheel steel counter-material in the wear couple. The wear resistance of bainitic steels depends upon the volume fraction of hard phase, such as carbide and martensite-austenite phase, for rolling-sliding as well as other types of dry wear loading. Pearlitic steel performs exceptionally well under certain rolling-sliding conditions, such as the majority seen in these tests, since the lamellar microstructure is modified so as to present a greater area fraction of carbide hard phase at the wear surface, a fraction in excess of bulk volume fraction. Recommendations are made for the dry wear applicability of the steels.

PREFACE

The work reported on in this thesis was carried out whilst I was employed as a research associate by the Department of Engineering at the University of Leicester. It is based on work undertaken for a contract for research between the University and British Rail Research, Derby. It was entirely funded by British Rail Research. I wish to thank British Rail and the Department of Engineering for a period of interesting employment and for the opportunity to write this thesis. In particular, I would like to thank British Rail Research for the kind loan of their wear testing machine as this provided a firm foundation for the research programme and for the construction of an in-house wear machine.

The Department of Engineering has a noble history in tribological studies based on the work of the late Jack F. Archard. This has been continued by my tutor, Dr. John H. Beynon, a senior lecturer and member of the Mechanical-Materials Research Group overseen by Prof. Alan R. S. Ponter. Above all else, I must thank John Beynon; his constant friendship, guidance and patience have been invaluable during the many trials and tribulations of this work. I'd also like to thank Dr. Alberto J. Perez-Unzueta for helpful discussion. Some undergraduate final year projects were linked to this research and the equipment described in this thesis. I wish to thank those students for their help, in particular, John R. Brightling.

I have been constantly grateful for the help and performance of *all* the Department's technical and academic related staff. They have produced work of the highest quality with great attention to detail. In particular, I remember Dave Linnett, who carefully manufactured most of the wear test discs and who sadly passed away a few years ago.

This thesis is dedicated to craftsmanship and helpfulness of all the technical and academic related staff.

I am also thankful for the full cooperation and assistance of staff at British Rail Research, in particular, Kevin J. Sawley, Mike B. P. Allery, Peter J. Bolton and

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I thank Marjorie Hengeveld, my family and friends for their constant encouragement and patience. Finally, thanks, and apologies, to those others who have helped me and who have not been mentioned.

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Chapter 3. THE CONTACT MECHANICS OF SOLID BODIES SUCH AS WHEEL ON RAIL.

Chapter 4. THE WEAR OF METALS: THEORY, MECHANISMS AND TESTING.

Chapter 5. RAIL DAMAGE.

APPENDED PAPERS

APPENDIX I

J. E. Garnham, J. R. Brightling and J. H. Beynon. "Rolling-sliding dry wear testing - A vibration analysis." *WEAR* 124 (1988) pp. 45-63.

APPENDIX II

J. E. Garnham and J. H. Beynon. "The early detection of rolling-sliding contact fatigue cracks." *Proc. 3rd. Int. Symp. on "Contact mechanics and wear in rail-wheel systems", 22-26/7/90, Univ. of Cambridge (UK).* Pub. *WEAR* 144 (1991) pp. 103-116.

APPENDIX III

J. E. Garnham and J. H. Beynon. "Dry rolling-sliding wear of bainitic and pearlitic steels." *WEAR* 157 (1992) pp. 81-109.

CHAPTER 1

INTRODUCTION

1.1 Background

The work described in this thesis was carried out under the terms of a research contract between British Rail and the University of Leicester's Department of Engineering. Its purpose was to complement previous work, carried out by British Rail Research[Bolton et al, 1982; Bolton & Clayton, 1984] on the rolling-sliding wear behaviour of a series of pearlitic rail steels, by examining the wear behaviour of alternative bainitic steel structures.

During the last three decades, increases in rail traffic speeds in Europe and Japan, and increases in axle loads on the heavy haul lines of primarily America, Asia and Australasia, greatly increased the wear and fatigue damage of rails, resulting in replacements in some curved track every few months, rather than after several years. The profile of a worn upper rail from a track curve is compared with a new rail profile in Figure 1.1. Additionally, recent rail vehicle designs had smaller diameter wheels and this further increased contact stresses on rails. These factors stimulated research into improved rail steel structures, optimised rail profiles, limited track curve lubrication and sophisticated track re-profiling (grinding) practices. Incremental improvements in all these areas have very recently helped to significantly increase rail lives, particularly on heavy haul tracks. An additional factor has been the traction control systems fitted to modern engines which limit wheel slip during acceleration and braking.

The contact area between a loaded wheel and a rail is small, around $1cm^2$ [Sawley, 1989], i.e. the system can be viewed as a large bearing race moving heavy loads with minimal resistance. As with ball bearing contacts, the small contact patch is subject to very high compressive contact stresses, up to 2 GPa on British Rail, and also high shear stresses due to applied longitudinal and lateral tractive forces with nominally dry contact. Rails, and their joining welds, are designed to resist wear, rolling contact fatigue, bending stresses (the rail can be viewed as an I-beam between two sleeper supports) and thermal stresses, due to climatic changes and welding. British Rail annually purchase the rail equivalent of between 1% and 3% of the track mileage, 20,000 miles[Sawley, 1989].

For most track locations, BS11[BS11, 1978] normal grade rail continues to be used. This has had a minimal change in composition (wt.%) over the years (Table 1.1), however steel cleanliness has greatly improved and the steel making process has changed from acid Bessemer, to basic open hearth and now to basic oxygen, with the production form changing from ingot to continuously cast. Modern rails, which will be joined by welding, are hot rolled and sectioned to lengths equivalent to three carriages long. These can be transported via specialised rolling stock to the welding site. Rails are subject to a tensile force as they are welded so as to eliminate any buckling at any subsequent high climatic temperatures.

Rail life in track curves, particularly on the upper, outer rail, is governed by its resistance to rolling-sliding wear, as here large lateral tractions are applied to the contact to guide vehicles around the bend. At particularly severe curves, higher strength rail steels are used to resist wear. These are normally harder grades of pearlitic steel, i.e., with refined structures obtained from either increased carbon and alloying additions, from controlled cooling from hot-rolling, from post hot-rolling heat treatment or from a combination of these factors. Rail weld cooling must similarly be strictly controlled to give near-equivalent structures. These higher grade steels have poor weldability and some, such as high chromium pearlitic steel rails, are often found bolted together.

Another part of the rail system subject to high wear, but of a different nature, is the rail crossing. Here two rails are blended to a sharp point, known as "the nose". This area is subject to severe impact wear ("batter") as passing wheels change direction. At severe crossings, British Rail have used cast austenic manganese steel to give improved batter resistance, however this steel is subject to various problems and cannot be welded[Frederick and Jones, 1980]. The search for an alternative batter resistant steel stimulated research into high strength, ductile, low carbon, low alloy bainitic steel structures[Callender, 1983], which would both resist impact wear and have good weldability. A successful steel was proposed and is now in use. Such steels do not require controlled cooling from welding. Typical compositions and strengths of current pearlitic rail steels are compared with those of a bainitic crossing steel in Table 1.2. A further development has been their use as railway wheels as, from the very high temperatures generated by any wheel skid, the bainitic structure is maintained during cooling. With pearlitic steels there can be a phase change to brittle martensite and subsequent spalling.

In the laboratory, bainitic steels were initially asssessed for wear resistance by cooled, pure sliding, low contact stress, pin on disc tests[Clayton et al, 1987]. These gave promising results. During these developments, rails were manufactured from similar bainitic steels and placed in curved track, however, their resistance to rolling-sliding wear proved poor[Sawley, 1986]. Other rail research indicated that bainitic and martensitic structures have poorer rolling-sliding wear resistance than pearlitic steels with equivalent, or slightly poorer, mechanical properties[Ichinose et al, 1978; Heller et al, 1982; Kalousek et al, 1985]. In order to better understand the microstructural mechanisms responsible for such rolling-sliding wear behaviour, without expensive, time-consuming track trials, British Rail funded the present work.

A further aspect of the research was to gain a better understanding of the nature of wear tests. It has to be constantly emphasised that wear resistance is *not* a bulk material property, it is related to the system within which wear performance is being assessed[Czichos, 1979] and to the material condition at, and very near, the wear interface. The mixed results experienced by British Rail with these bainitic steels illustrates this point.

Most rail rolling-sliding wear research has been carried out on a machine developed by Amsler[Amsler, 1922], known as the Amsler machine, or on a derivative. Contact is via two cylindrical discs of equal width, usually made from rail and wheel steels, respectively. Discs are loaded via a calibrated spring. Slide is induced via a fixed gear, rotational speed differential applied each disc shaft. Most Amsler tests at British Rail Research utilised forced air cooling of the contact, both to cool the discs and to clear debris from the contact, as observed on track. This was highly significant as many reported wear results, involving changes to far severer wear regimes, have been mainly influenced by large temperature rises at the contact. A modified Amsler machine was made available by British Rail for this research.

A further significant part of the work described in this thesis was the construction and use of an alternative rolling-sliding wear machine to the Amsler. This machine, the **LE**icester **RO**lling and **S**liding wear machine - LEROS, was designed to give better control of wear system variables and extend the test condition range. It was also useful and informative to compare wear behaviour on two machines. Comparative tests on simple pin on disc machines have revealed how variable wear results can be[Czichos et al, 1987, Almond & Gee, 1987].

1.2 Thesis outline.

Each chapter of the thesis is an independent section with references, tables and figures. This facilitates treatment of each major topic. Chapter 2 examines bainitic steel structures. The precise mechanism of the transformation from austenite to bainite during cooling is still subject to some intense academic debate. This area is reviewed. Conventional medium carbon steels form structures known as upper and lower bainite, each with distinctive carbide distributions. Less well known, and used, are low alloy, low carbon steels which transform to bainitic structures with no carbide distributions. The absence of a carbide-ferrite interface results in these steels having distinctly different ductile properties. These structural differences are reviewed. Three bainitic steels were produced for the present work with a range of carbon contents. These were balanced by alloying additions with the aim of producing steels with similar transformation temperatures. One steel contained carbide, the other two were carbide free.

In Chapter 3 the complex subject of contact mechanics is reviewed in some detail. This is fundamental to most moving engineering contacts, including bearing technology and, similarly, the operation of rail vehicles. The wheel-rail elliptical contact area changes in shape, normal stress loading and tractive stress loading as the lateral position of the wheelset across the track alters. In this chapter, the initial theories of Hertz[1882] are examined for an elastic analysis of the elliptical contact between wheel and rail and, also, the rectangular contact between cylindrical discs as these have been used for most laboratory rolling-sliding dry wear tests. The relative movements of the contacting bodies both on a minor scale within the contact, and as bulk movements outside the contact, are examined, together with the implications for material behaviour and the control of rail vehicle movements. Stress distributions arising from Hertzian contacts are examined, together with the implications of sliding, of rolling-sliding and of the change to non-Hertzian plastic behaviour with concepts of yield, shakedown and ratchetting.

Chapter 4 examines in some depth the complex subject of wear, particularly the theories and mechanisms of metallic wear, the relationship with friction, and the inter-relationships between the various wear mechanisms and material mechanical properties. Fundamental work on these relationships was carried out by the late Dr. Archard whilst with this university department[Archard, 1980]. Wear testing procedures are briefly reviewed.

Chapter 5 examines the various forms of damage observed on rails, including rolling-sliding wear, rolling contact fatigue and the formation of periodic undulations ("corrugations"). These can all be generated on twin-disc wear test machines. The microstructural implications of such damage are considered.

Chapters 6 and 7 respectively describe the Amsler and LEROS wear machines used for the present work, plus their test programmes and the vibration analyses carried out on each machine.

Chapter 8 gives the wear results from both machines. These include wear curves, from the respective grouping of wear patterns, and the appearance and circumferential (Talyrond) profiles of some worn discs. Various disc surface features are considered, including periodic undulations and ripples, and the inter-relationship between track plastic deformations and the form of wear debris generated.

Chapter 9 describes the microstructures of test discs from the respective groupings, including the effect of zero sliding, high sliding and low contact stress, vice versa and various combinations of both. Optical observations are supplemented by some limited electron (SEM and TEM) micrographs.

Factors from all these chapters are discussed in Chapter 10 where reasons are put forward for the lack of correlation between the bulk mechanical properties of the pearlitic and bainitic steels and their wear performance. Results from other workers are considered, including the testing of bainitic steels under conditions not covered by the tests described in the present work. Conclusions and some recommendations for further work are given in Chapter 11.

Three publications, written by the author and co-workers, are appended. Appendix I[Garnham, Beynon & Brightling, 1988] describes the initial vibration analysis of the Amsler machine. Appendix II[Garnham & Beynon, 1990] describes the further development of the LEROS machine for detecting rolling contact fatigue cracks in rail steels, early in their life. Appendix III[Garnham & Beynon, 1992] briefly covers much of the present work, the dry rolling-sliding wear of pearlitic and baintic steels.

1.3 References.

Almond, E.A. and Gee, M.G. (1987). "Results from a U.K. inter-laboratory project on dry sliding wear." *WEAR* 120, pp. 101-116.

Amsler, A.J. (1922). "Abnützungsmaschine für Metalle (Wear machine for metals)." *Z. VDI* 66, pp. 377-378.

Archard, J.F. (1980). "Wear theory and mechanisms." Wear Control Handbook, eds., M.B. Peterson and W.O. Winer, pub. ASME, New York, USA., pp. 35-80.

Bolton, P.J., Clayton, P. and McEwen, I.J. (1980). "Wear of rail and tyre steels under rolling-sliding conditions." *Proc. ASME/ASLE Lubrication Conf., San Franscisco, USA, 18-21/08/80*. Pub. *ASLE Trans.* 25 (1), pp. 17-24.

Bolton, P.J. and Clayton, P. (1984). "Rolling-sliding wear damage in rail and tyre steels." *WEAR* 93, pp. 145-165.

BS11 (1978). British Standards Institution.

Callender, W.R. (1983). "Bainitic steels for railway applications." *PhD Thesis*, University of Sheffield, UK.

Czichos, H. (1979). "Tribology - a systems approach to the science and technology of friction, lubrication and wear." Tribology Series 1, pub. Elsevier, Amsterdam, The Netherlands.

Czichos, H., Becker, S. and Lexow, J. (1987). "Multi-laboratory tribotesting: Results from VAMAS programme on wear test methods." *WEAR* 114, pp. 109-130.

Frederick, C.O. and Jones, E.G. (1980). "A review of rail research on British Rail." Paper presented to the January 1980 meeting of the Transportation Research Board, Washington DC, USA.

Garnham, J.E., Brightling, J.R. and Beynon, J.H. (1988). "Rolling-sliding dry wear testing - a vibration analysis." *WEAR* 124, pp. 45-63 (appended - Appendix I).

Garnham, J.E. and Beynon, J.H. (1990). "The early detection of rolling-sliding contact fatigue cracks." *Proc. 3rd. Int. Symp. on "Contact mechanics and wear in rail-wheel systems", 22-26/7/90, Univ. of Cambridge (UK)*. Pub. *WEAR* 144 (1991), pp. 103-116 (appended - Appendix II).

Garnham, J.E. and Beynon, J.H. (1992). "Dry rolling-sliding wear of bainitic and pearlitic steels." *WEAR* 157, pp. 81-109 (appended - Appendix III).

Heller, W. and Schweitzer, R. (1982). "Hardness, microstructure and wear behaviour of rail steels." *Proc. 2nd. Int. Conf. on "Heavy Haul Railways", Colorado Springs, CO, 25-29/9/82*, Assc. of American Railroads and American Soc. of Mech. Engrs., pp. 282-286.

Hertz, H. (1882). "Über die Berührung fester elastischer Körper (On the contact of elastic solids)." *J. reine und angewandte Mathematik* 92, pp. 156-171. (For English translation - Miscellaneous Papers by H. Hertz, eds. Jones and Scott, pub. Macmillan, London, 1986.)

Ichinose, H., Takehara, J., Iwasaki, N. and Ueda, M. (1978). "An investigation on contact fatigue and wear resistance behaviour in rail steels." *Proc. 1st. Int. Conf. on "Heavy Haul Railways", Perth, Australia, September, 1978.* Inst. Engrs. Austr. and Austr. Inst. Mining and Metallurgy, 1978, Session 307, Paper I.3.

Kalousek, J., Fegredo, D.M. and Laufer, E.E. (1985). The wear resistance and worn metallography of pearlite, bainite and tempered martensite rail steel microstructures of high hardness." *Proc. Int. Conf. on "Wear of Materials '85", Vancouver, BC, 14-18/4/85.* Pub. *WEAR* 105 (3), 1985, pp. 199-222.

Perez-Unzueta, A.J. (1992). "Microstructure and wear resistance of pearlitic rail steels." *PhD Thesis*, University of Leicester.

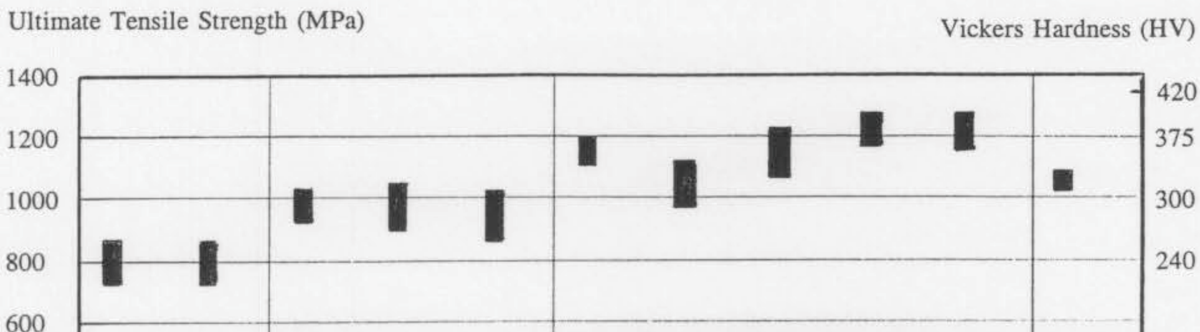
Sawley, K.J.[British Rail Research, Derby, UK] (1986). Personal communication.

Sawley, K.J. (1989). "Materials in railway engineering." *Metals and Materials* 5 (4), pp. 210-214.

Weston, J. and Sawley, K.J. (1987). "Rolling-sliding wear of a range of bainitic steels." British Rail Research results; not published. Personal communication.

Year	C	Mn	Si	S	P
1922	0.55-0.65	0.8 max	0.10-0.30	0.05 max.	0.04 max.
1985	0.45-0.60	0.95-1.25	0.05-0.35	0.04 max.	0.04 max.

Table 1.1 The minimal change in the BS11 normal grade steel specification with time[from Sawley, 1989].



wt%	Plain carbon grades.		Wear-resistant grades.			High strength, high wear resistance grades					Bainite crossing
	A	B	C	D	E	F	G	H	I	J	K
C	0.55	0.50	0.75	0.65	0.75	0.75	0.75	0.75	0.75	0.75	0.09
Si	0.25	0.25	0.25	0.25	0.25	0.25	0.90	0.70	0.80	0.25	0.28
Mn	1.00	1.00	1.00	1.50	0.90	1.00	1.00	1.00	1.00	0.90	0.64
Cr	-	-	-	-	-	1.00	-	1.00	1.00	-	1.90
V	-	-	-	-	-	-	-	-	0.10	-	-
Ni											2.80
Mo											0.50
B											0.0013

Above: Nominal compositions.

KEY	GRADES
A	BS11 normal grade.
B	UIC860 grade 70.
C	BS11 wear resistant grade A / UIC860 grade 90A.
D	BS11 wear resistant grade B / UIC860 grade 90B.
E	AREA standard carbon grade.
F	British Steel 1% Cr grade.
G	UIC860 S1000.
H	UIC860 S1100.
I.	UIC860 S1200.
J	AREA heat treated, high strength grade.
K	Early specification for a British Rail bainitic crossing.

Table 1.2 Nominal compositions and strengths of British (BS), European (UIC) and North American (AREA) pearlitic rail steels[after Perez, 1992], compared with an early British Rail bainitic crossing rail steel.

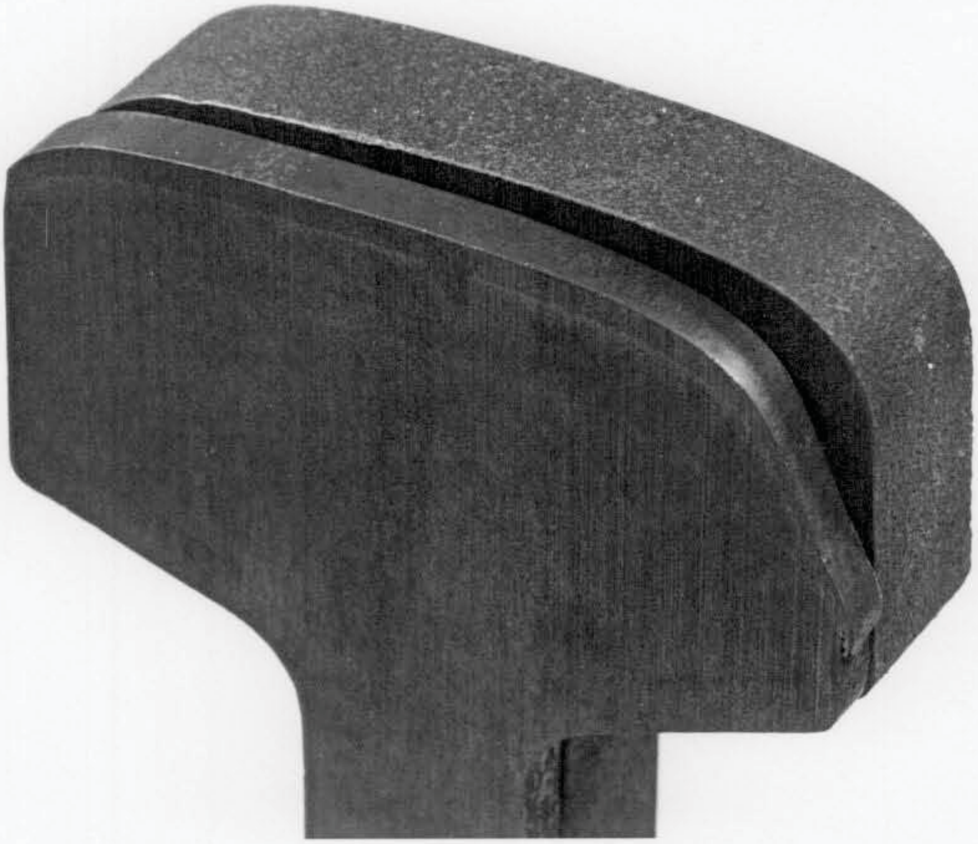


Figure 1.1 A comparison between new and worn rails. This shows the typical form of severe gauge face wear that occurs on outer rails, installed in tight curves, on the British Rail network[print kindly donated by British Rail Research].