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INNOTRACK

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Thematic Priority 6: Sustainable Development, Global Change and Ecosystems

WP 4.3.6 – Characterisation of Microstructural Deformation as a function of Rail Grade

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RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

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Glossary

EBSD	Electron back scatter diffraction
KAM	Kernal Average Misorientation
RCF	Rolling contact fatigue
SCL	Surface crack length, measured in mm
POI	Position of initiation, measured as the distance in mm from the active side of head
SoH	Side of Head
SEM	Scanning Electron Microscope
DB	Deutsche Bahn
NR	Network Rail
vas	voestalpine schienen GmbH

Executive Summary

In recent years, a very significant volume of work and research resources have been devoted to the study of wheel rail contact conditions through numerical and vehicle dynamic simulations. The improved understanding has enabled the determination of optimum wheel and rail profiles and improved vehicle designs to reduce the imposed stresses and thereby make a welcome contribution towards increasing rail life. However, a parallel and equally important avenue of research is to establish the metallurgical properties of the rail that would make it more resistant to the prevailing degradation mechanisms.

It is this metallurgical context that made it necessary to establish an objective methodology for assessing microstructural “damage” caused by passing vehicles. It should also be recognised that although a measure of the energy input in the contact patch has given encouraging correlation with observed rolling contact fatigue (RCF) damage, it is an empirical approach that does not provide any guidance for the development of more “damage” resistant rail grades. Furthermore, knowledge of the true depth of “damage” from the running surface is beneficial for the determination of the magnitude of metal removal that may be necessary to restore the undamaged original microstructure.

Although research by rail manufacturers has lead to the development of a wide range of rail grades, their adoption by the Infrastructure Managers has been slow and limited. It is, therefore, imperative that the comparative benefits of the use of the available rail steels are established scientifically to enable their use under the appropriate duty conditions to minimise life cycle costs of track maintenance. The assessment of the level of susceptibility to microstructural “damage” of the various rail grades under similar duty conditions is considered desirable to establish the guidelines for the optimum selection of the available rail steels.

Electron Back Scatter Diffraction technique has been applied in a novel manner for the assessment of microstructural misorientation that results from the stresses imposed by rail wheel contact. The key conclusions from the work reported are:

1. Using control samples of **UNUSED** as-manufactured rail, it has been shown that the degree of misorientation measured by EBSD technique is minimal from the surface to the measured maximum depth of 5mm. Since hot rolled rails undergo high temperature static recrystallisation immediately after rolling, the minimal microstructural misorientation measured by the developed EBSD technique demonstrates the validity of the technique. In the case of **UNUSED** as-manufactured heat treated rails, the degree of the measured microstructural deformation (“damage” relative to unstrained microstructure) is slightly higher than that for as rolled non-heat treated grades, which is probably a reflection of the finer pearlitic microstructure. Consequently, EBSD analysis has been shown to be a credible technique to determine the magnitude of microstructural misorientation and its use for assessing the magnitude of “microstructural damage” from the passage of traffic. The proposed technique is the only direct and objective measure of accumulated “damage” imparted by wheel-rail interaction and is far more discriminating than the currently used technique of microhardness measurements.
2. The most important finding of this work is the determination of the depth at which the microstructural misorientation in trafficked samples reaches that of unused rail i.e. the depth of the “damaged layer”. The values indicate a decreasing depth of “damaged layer” with increasing hardness of the rail with R370CrHT and R400HT grade rails showing “damage” depths of <1mm. Clearly, the very limited depth of the “damaged layer” in the premium harder rail steel grades suggests that the “damaged layer” could be removed by light grinding to expose undeformed (“undamaged”) microstructure.
3. The assessment of samples from twin disk tests, employing an unusually large number (5000) of dry cycles, has also shown a decrease in depth of “damaged layer” with increasing rail hardness. However the absolute magnitude of depths were significantly less than the corresponding figures for trafficked samples. This has been attributed to the removal of material as a result of the high wear during the dry cycles. It has also be

suggested that the shallower depth of the deformed/stressed layer may be a reflection of the contact geometry. However, a reduction in the number of dry cycles from 5000 to just 250 in the Corus Twin Disc tests has given depths of “damaged layer” that are similar to those observed in trafficked samples and hence provide confidence in this simple test to provide reliable comparative properties for the various rail grades.

4. The microstructural deformation measured from the gauge corner of the test samples from the roller rig at vas reflects good correlation with trafficked samples. However, for all grades examined, the microstructural deformation from the top of the head locations was appreciably less and achieved the value of the control sample at a much shallower depths than those in trafficked rails of the corresponding grade. This is probably a result to the specific contact and resulting stress condition.
5. Based on the assessment to date, it is concluded that microstructural deformation reflects the specific loading conditions and that the optimum selection of rail grades for the wide variety of loading conditions that exist on any railway network should be based on the performance of the rail grades under very closely controlled test conditions as undertaken in this programme. The rail grades in order of increasing resistance to microstructural deformation are: R220, R260, R350HT, with the highest resistance being provided by R370CrHT and R400HT. The advantages that could be realised in the appropriate track locations are:
    - Maintenance of the desired crown profile for longer periods to ensure the desired rail-wheel contact
    - Increased proof strength to resist plastic deformation in a railway network designed for higher speed passenger traffic and increasingly being asked to carry more freight traffic at lower speeds
    - Increased resistance to the initiation of rolling contact fatigue as demonstrated by the laboratory tests and the Innotrack developed degradation models for RCF resistance based on a wide range of track trials
    - The much lower depth of microstructural “damage” that can potentially be removed more effectively through single pass grinding at longer intervals.

The above knowledge of the resistance to microstructural deformation has been combined with rail degradation algorithms derived from extensive track trials to arrive at the “D4.1.5 Guidelines for Rail Grade Selection”

It is recommended that the work be extended to examine the effect of the magnitude of traffic on the depth of the “damaged layer” using controlled samples from track. Further research is also recommended to establish a correlation between the measured KAM values and the accumulated strain.

1 Introduction

In recent years, a very significant volume of work and research resources have been devoted to the study of wheel rail contact conditions through numerical and vehicle dynamic simulations. The improved understanding has enabled the determination of optimum wheel and rail profiles and improved vehicle designs to reduce the imposed stresses and thereby make a welcome contribution towards increasing rail life. However, a parallel and equally important avenue of research is to establish the metallurgical properties of the rail that would make it more resistant to the prevailing degradation mechanisms.

It is this metallurgical context that made it necessary to establish an objective methodology for assessing microstructural deformation ("damage" relative to the unstrained microstructure) caused by passing vehicles. It should also be recognised that although a measure of the energy input in the contact patch has given encouraging correlation with observed occurrence of rolling contact fatigue (RCF) cracks, it is an empirical approach that does not provide any guidance for the development of more RCF resistant rail grades. Furthermore, knowledge of the true depth of "damage" (the depth to which the microstructure is deformed relative to the unstrained microstructure) from the running surface is beneficial for the determination of the magnitude of metal removal that may be necessary to restore the undamaged original microstructure.

Although research by rail manufacturers has lead to the development of a wide range of rail grades, their adoption by the Infrastructure Managers has been slow and limited. It is, therefore, imperative that the comparative benefits of the use of the available rail steels are established scientifically to enable their use under the appropriate duty conditions to minimise life cycle costs of track maintenance. The assessment of the level of susceptibility to microstructural damage of the various rail grades under similar duty conditions is considered desirable to establish the guidelines for the optimum selection of the available rail steels.

The programme of work reported in this document is a novel application of Electron Back Scatter Diffraction techniques developed and successfully employed in other areas of metal research. It has been applied to measure the magnitude of microstructural deformation in range of samples taken out of track and those tested under controlled laboratory tests. The technique employed has been described in detail in an earlier deliverable[1] (D4.3.2) but further background justifying the use of EBSD techniques is included in this document to aid better understanding of the results and demonstrate the robustness and usefulness of the technique. The work is part of the wider programme of "Innovative Laboratory Tests for Rail Steels" undertaken within WP4.3 of Innotrack and further background information about the samples used in this study can be obtained from the other deliverables[2-8] of this WP.

2 Background and Justification

The microstructure of virtually all rail steels in use in railway networks throughout the world is pearlitic. Pearlite is a lamellar arrangement of α-ferrite and cementite formed in a eutectoid reaction from austenite, some proeutectoid ferrite is also present in microstructure of compositions with carbon contents lower than eutectoid composition in the iron-carbon phase diagram. Such a microstructure from untrafficked Grade R260 rail is shown in Figure 1.

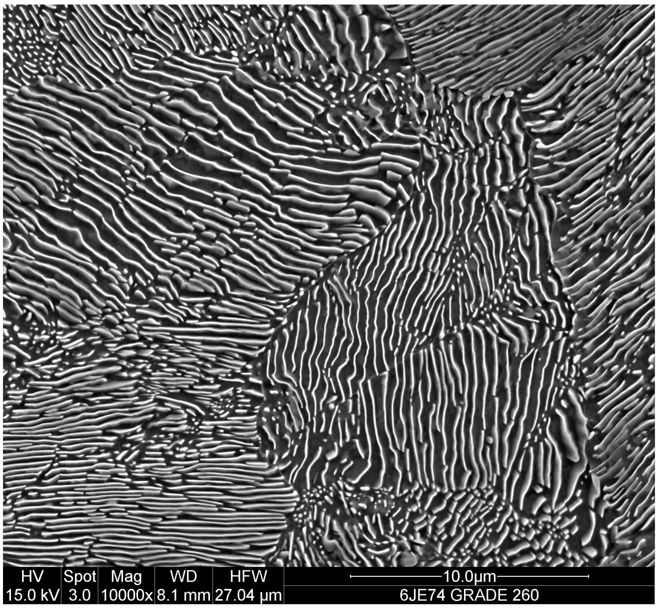
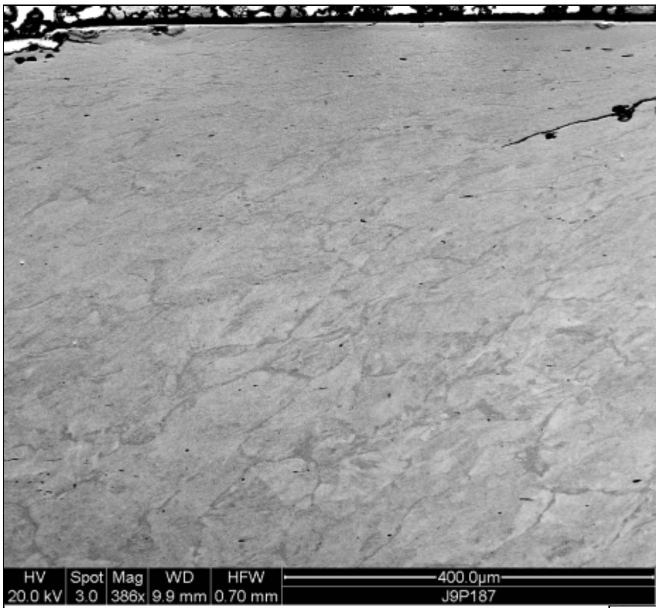
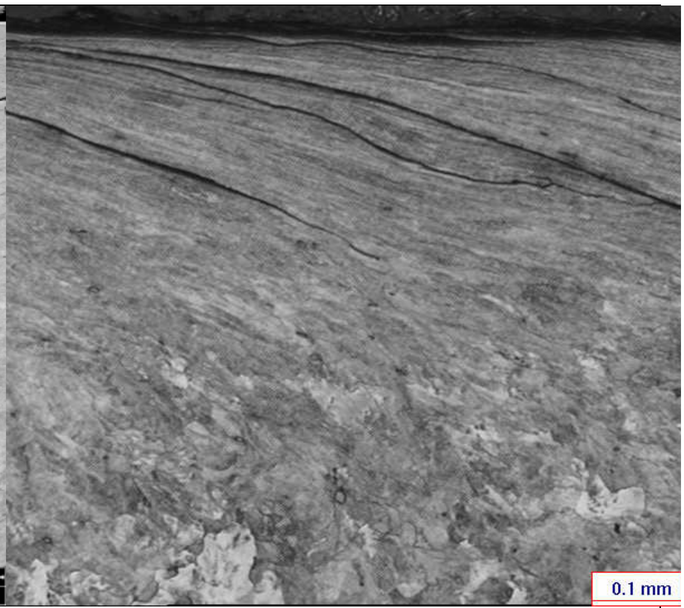


Figure 1 Scanning Electron Micrograph of R260 Rail Steel

The different orientations of the lamellar structure and of the pearlite nodules are evident even in this 2D view of the microstructure. The drive for improving the performance of rail steels has been centred round increasing the hardness of the pearlitic microstructure through alloying and/or heat treatment to reduce the interlamellar spacing of the pearlitic microstructure. The increased resulting hardness has been shown to be well correlated to the key performance parameters of resistance to wear and rolling contact fatigue. However, hardness is a macro property reflecting the properties of the microstructural constituents of pearlitic ferrite and cementite, the interlamellar spacing and pearlite nodule or colony sizes. Similarly, the various other rail steel properties such as tensile strength and ductility, fracture toughness, and fatigue crack growth rates included in specifications are with reference to the as supplied untrafficked microstructure.

Figures 2 and 3 show the microstructure of trafficked samples from the track and that following twin disc testing in a laboratory[8]. Microstructural deformation under traffic/loading is apparent in both cases but the assessment of the magnitude of “damage” or change has been restricted to theoretical considerations of contact conditions and measure of the energy input with limited consideration of the metallurgical characteristics of the various rail grades. In practical terms, the magnitude of the depth of work hardening, as established by micro hardness measurements, has been used. Representative results for Grades R220 and R350HT rail grades from the UK network are shown in Figure 4. The results suggest that the parent rail hardness is encountered at relatively shallow depths of ~1mm.





Deformed Microstructures

Figure 2 Trafficked Grade R220 Rail	**Figure 3 R260 Grade steel after 5000 dry + 5000 Wet Cycles in Twin Disc Test[8]**

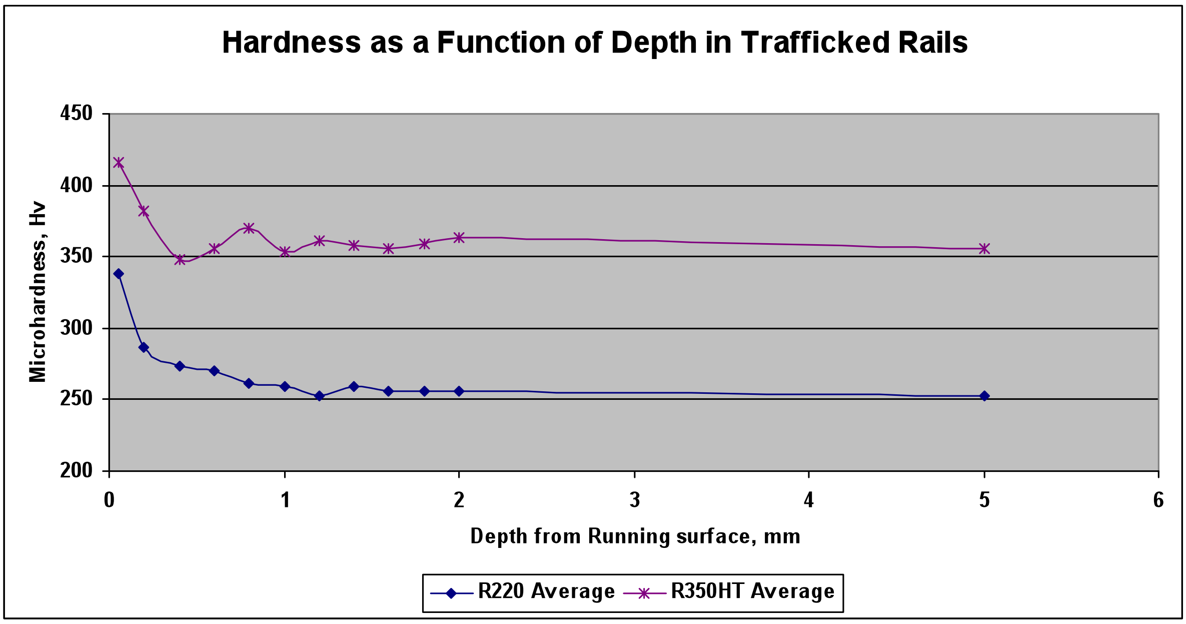


Figure 4 Assessing Microstructural Deformation Through Measurement of Micro Hardness

Furthermore, pearlite is a three-dimensional microstructure and the performance of the steel at the rail wheel interface needs to consider the properties of the microstructural constituent and its orientation to the interface. The relevance of this need is apparent from the 3D representation of pearlite[9,10] shown in Figures 5 and 6.

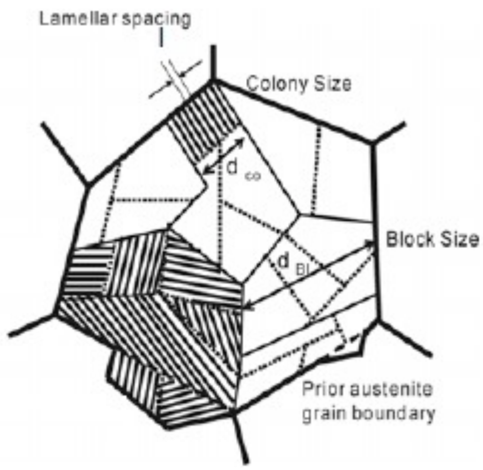


Figure 5 Schematic of Pearlite Microstructure

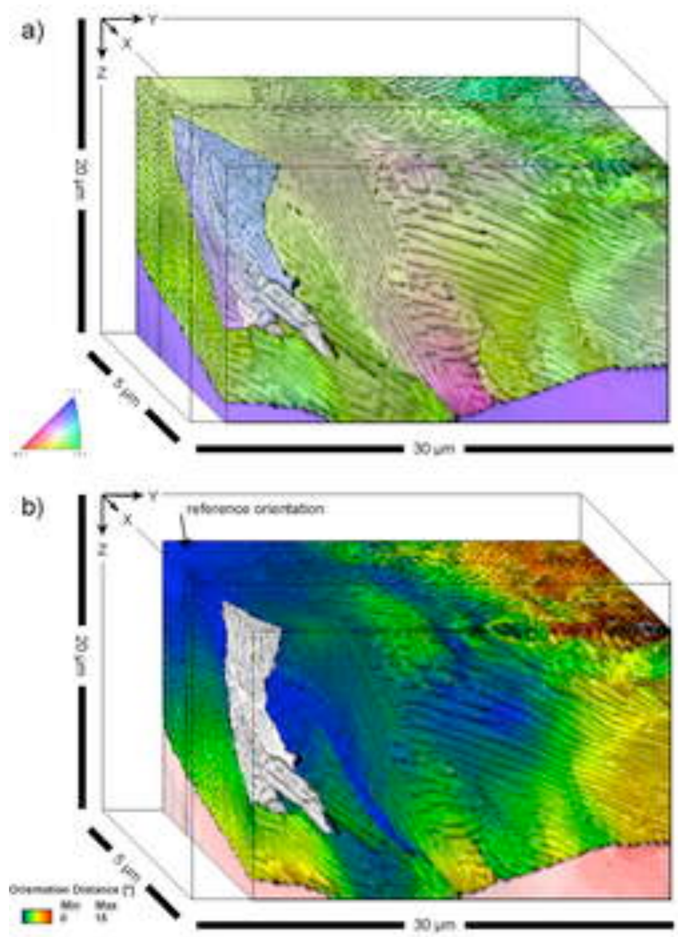
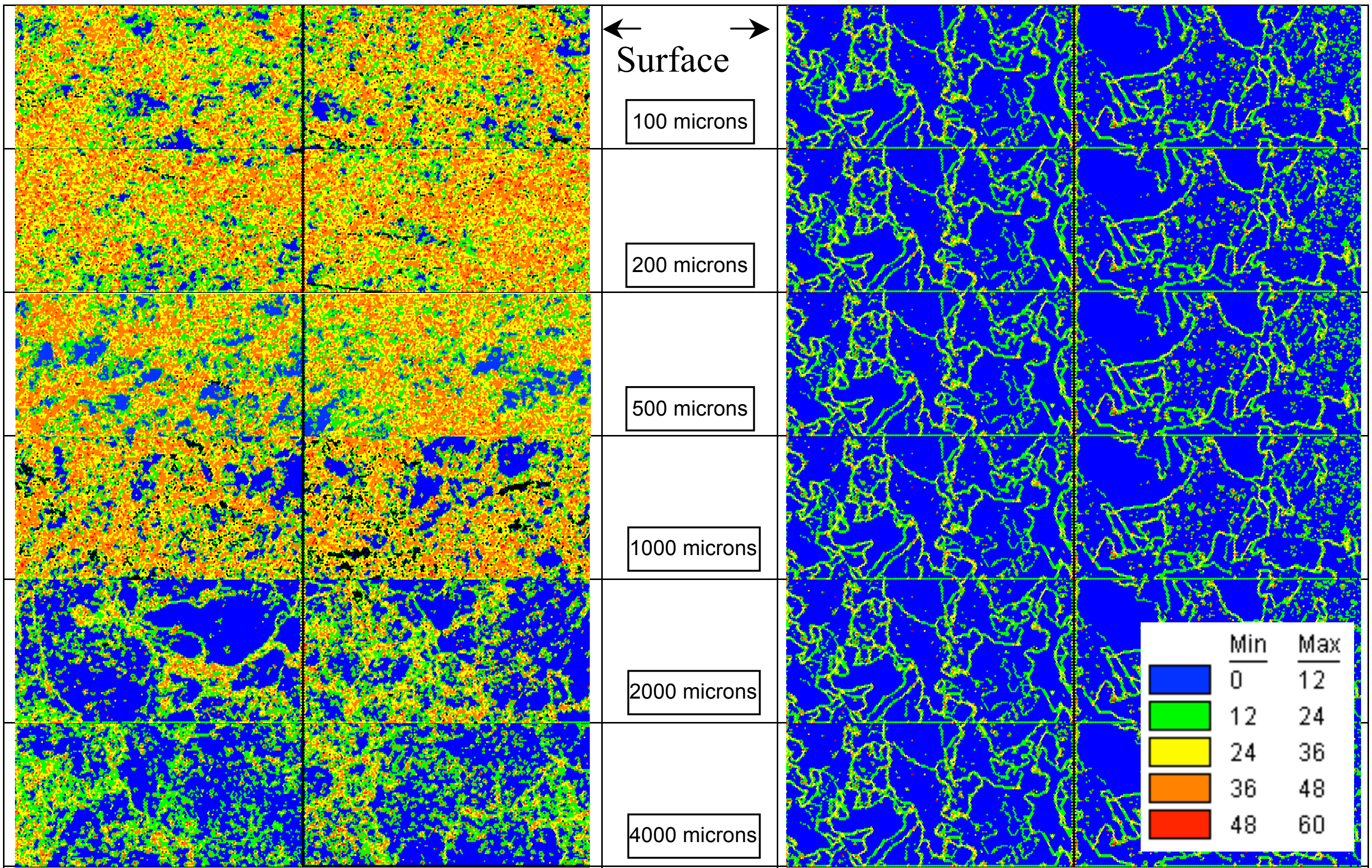


Figure 6 3D Microstructure of Pearlite using EBSD[3]

Figure 5 is a schematic of the pearlite microstructure[9] showing some of the key parameters that can influence overall properties and performance. Figures 6a and 6b are results of 3D investigations of the pearlitic microstructure using EBSD techniques[10]. The colour comprises the image quality (grey value) and a colour code for the crystal direction parallel to the X-axis of the sample. The outer lines indicate the measured volume. Figure 6b shows the same microstructure as shown in Figure 6a but indicates local orientation changes across the volume. Although further details of the techniques employed are described by Beckschäfer of Max Planck Institute[10], the 3D representation of the pearlitic microstructure makes it abundantly apparent that at any given point, either of the two microstructural constituents could be present in varying proportions and orientations at the wheel-rail contact. Consequently, the response of the various rail grades to the stresses imposed at the rail wheel interface needs to consider the properties of the microstructural constituents at the running surface and the deformation of the microstructure as a function of depth. The assessment of this latter aspect for a range of rail steel grades is the subject of the current investigation employing electron backscatter diffraction techniques. Although details of the methodology employed are given in an earlier deliverable[1] (D4.3.2), the technique uses the Scanning Electron Microscope (SEM) to obtain information about the crystallographic structure of the material. When electrons strike a crystalline sample, they are diffracted and form a pattern that is characteristic of the structure of the material. Information that can be obtained from the diffraction pattern includes grain misorientation, grain boundary orientation and texture. This technique has been applied to study microstructural deformation in trafficked rail and in samples subjected to a range of laboratory tests using a parameter called 'Kernel Average Misorientation' (KAM) that enables colour coding of the microstructure according to the average misorientation between a point and its 6 equidistant neighbours within a hexagonal grid.

The robustness of the technique for the study of microstructural deformation is apparent from Figure 7 that compares the KAM maps for Grade 220 rails in the untrafficked and trafficked conditions, the latter with severe Rolling Contact Fatigue (RCF) cracks. The colour coding reveals the high degree of misorientation in the surface layers of the trafficked samples with the degree of misorientation decreasing with increasing depth from the running surface. In contrast, the untrafficked sample exhibits the lowest degree of misorientation reflecting the statically recrystallised structure of the as rolled microstructure.



Trafficked R220 Rail - Severe RCF (J1P58) **Untrafficked R220 Rail (J4E170)**

Figure 7 Comparison of R220 Rails in Trafficked and Untrafficked Conditions using EBSD

3 Project Objectives and Scope

The following two are the primary objectives of the work undertaken:

1. To undertake comparative assessment of the magnitude of microstructural deformation in trafficked rail samples from a range of available rail steel grades.
2. To compare microstructural deformation observed in trafficked samples taken out of commercial track with those from a range of laboratory tests and covering a range of rail grades.

3.1 Matrix of Samples Examined

The matrix of samples examined is presented in Tables 1a and 1b below for both trafficked samples and those from the various laboratory test rigs. In case of the samples from track, brief details of in-track service history are included where available. However, it should be emphasized that the matrix of samples from track must not be regarded as fully controlled samples with comparable pedigree. Instead, they cover a wide range of difference in track radii and cant. Furthermore, although the magnitude of traffic carried is known, the type, wheel profiles, and the track support conditions that have a direct effect on the stresses experienced by the rail are not known. Similarly, the site history of rail grinding and other associated track maintenance that can affect the magnitude of deformation of the microstructure is also not known. Although the potential impact of the lack of such information on the conclusions of the study is acknowledged, the variety of samples from different sites and railway networks provides a relatively reliable basis for examining the deformation behaviour of the various rail steel microstructures. Equally, the emerging trends can be verified and further substantiated through the more controlled examination of samples from laboratory wear and rolling contact fatigue tests.

Table 1a Trafficked Rail SAMPLES FOR EBSD Analysis

QA Code	Location	Sample Type	Rail Grade	Rail Year	Rail Section	Track Radius	Traffic, MGT	RCF Category
J4E170	NA	Untrafficked - Control	R220	NA	56E1	NA	NA	NA
J1P65	NR, Newton Hall	Trafficked	R220	1989	56E1	1100	144	Clear
J9P187	NR, Lamington	Trafficked	R220	1983	56E1	1400	115	Light
J9P188		Trafficked	R220	1983	56E1	1400	115	Moderate
J9P189		Trafficked	R220	1983	56E1	1400	115	Heavy
J1P58/2	NR, Harringay	Trafficked	R220	1964	56E1	960	616	Severe
7JP10R	NA	Untrafficked - Control	R260	NA	56E1	NA	NA	NA
6JE74		Untrafficked - Control	R260	NA	56E1	NA	NA	NA
7JP10	Offenbach, DB	Trafficked	R260	1994	54E3	1200	200	Light
7JP11		Trafficked	R260	1994	54E3	1200	200	Moderate
7JP12		Trafficked	R260	1994	54E3	1200	200	Heavy
7JP13		Trafficked	R260	1994	54E3	1200	200	Severe
J2P98	UK, Slabtrack	Trafficked	R260	1996	UIC54	1400	118	Severe
J4E197	NA	Untrafficked - Control	350HT	NA	56E1	NA	NA	NA
J1P102	NR, Southside	Trafficked	350HT	1992	56E1	800	114	Light
8JP03	DB, Kerzell,	Trafficked, Ground 2004	350HT	2003	60E2	1436	75 since grinding	RCF
J1P28/2	Hatfield	Trafficked	350HT	1995	56E1	1500	78	Severe
7JP8	NA	Untrafficked - Control	R370CrHT	NA	54E1	NA	NA	NA
7JP28	Line Maarn - Lunettentrack, ProRail	Trafficked	R370CrHT	2000	54E1	2275	90	Severe

Table 1b Samples from Laboratory Tests for EBSD Analysis

QA Code	Sample Type	Rail Grade	Comments
INR24 7TR19C	SUROS	R260	5000 Dry
INR30	SUROS	R350HT	5000 Dry
INR10 9TR003A	SUROS	R350HT	5000 Dry
INR1 7TR35A	SUROS	400 HB	5000 Dry
VA400(1)	SUROS	R400HT	5000 Dry
INR23 7TR19B	SUROS	R350HT	5000 Dry + 5000 Wet
INR31	SUROS	350 HT	5000 Dry + 5000 Wet
INR11 9TR003B	SUROS	R350HT	5000 Dry + 5000 Wet
INR2 7TR35B	SUROS	R370CrHT	5000 Dry + 5000 Wet
VA400(3)	SUROS	R400 HT	5000 Dry + 5000 Wet
INR22 7TR19A	SUROS	R260	15000dry
INR25	SUROS	R260	15000 dry with R8T wheel
INR34	SUROS	R350HT	15000dry
INR12	SUROS	R350HT	15000dry
INR3 7TR35C	SUROS	R370CrHT	15000dry
VA400(2)	SUROS	R400HT	15000dry
INR26	SUROS	R260	20000 Wet
INR36	SUROS	R350 HT	20000 Wet
INR16	SUROS	R350 HT	20000 Wet
INR7	SUROS	R370CrHT	20000 Wet
INR40	SUROS	R400HT	20000 Wet
4TR332	Corus Twin Disc	R260	250 dry then wet till initiation
7TR114	Corus Twin Disc	R370CrHT	
8TR125C	DB Test Rig A	R260	300-400 MGT in total but grinding undertaken - Centre
8TR125G	DB Test Rig A, RCF free	R260	Gauge corner - Crack free
8TR125G	DB Test Rig A, RCF Crack	R260	Gauge corner - Within RCF crack
8JPO2 Top	DB Test Rig C	R260	20 MGT with increasing loads
9TR109C	VAS RIG	R260	Gauge corner
9TR110C	VAS RIG	R350HT	
9TR111C	VAS RIG	R370CrHT	
9TR109T	VAS RIG	R260	Top of rail
9TR110T	VAS RIG	R350HT	
9TR111T	VAS RIG	R370CrHT	
9TR112T	VAS RIG	R400HT	

3.2 EBSD Analysis Assessment Methodology

The basic details of the analysis technique have been described in an earlier report[1]. However, a change in the application of the technique was needed for the examination of some of the samples from the laboratory tests since they exhibited much shallower depths of microstructural deformations.

Initially, EBSD data was obtained from two areas at increasing depths from the running surface. Each area measured 160x80 micron and was collected at 1micron step length. As detailed in the earlier report[1], the average 'Kernel Average Misorientation' value for each area was obtained from the collected EBSD data. This technique has been used successfully for all samples from track and laboratory tests except those from the SUROS twin disk unit undertaken by University of Newcastle. Further details of which and the other laboratory tests are included in separate Innotrack Project deliverables[6-8]. The depth of deformation in the SUROS samples was much shallower and typically only 3 measurements could be made in the deformed layer using the previous methodology. It was felt that a more depth sensitive solution was required.

In order to address this, a single area 500 micron wide and up to 1000 micron deep from the surface was scanned at 1micron step length and the KAM map generated (see Figure 8 for an example). A bespoke analysis technique was developed to export the KAM value for each point and calculate the average for each scan line shown in the map. The corresponding plot of this raw KAM data from Figure 8 is shown in Figure 9.

Each blue point represents the average of 500 KAM values from each scan line with a nominal separation of 0.83 micron. Each red point represents the averaged KAM values from two 160x80 micron areas at that particular depth. As can be seen there is good agreement between the two datasets.

However, the appearance of the deformation in Figure 8 can be misleading. A lot of the high KAM values very close to the surface are due, in part, to non-indexable or indexed points with low confidence in the solution. Despite the ability of the FEG-SEM and careful preparation leading to EBSD patterns being obtained from highly deformed microstructures, there is still an upper limit where it is not possible to obtain accurately or index faint patterns. A measure of how well a pattern has been indexed is the 'Confidence Index', or CI. It is generally accepted that a CI>0.1 (up to the maximum of 1.0) represents a well imaged and indexed pattern. For the purposes of this work it has been necessary to stretch this definition to a CI>0.05 when we take into consideration that the structure is heavily deformed.

The raw dataset was then processed to exclude all points with a CI value <0.05. A side-effect of this is to produce KAM values of zero, where a well indexed point has no well indexed neighbours; in such cases, the KAM value cannot be calculated. The windows application used to calculate the average KAM value per scan line was modified in order to give the option to include or exclude these zero KAM values from the averaging calculation. These two new sets of data are also shown in Figure 9. Where these points coincide well, there is very little effect of excluding or including zero KAM values. This means that a high proportion of the points are reliably indexed and that there are relatively few 'bad' zero KAM points. Where this situation changes is near the surface, at less than ~50 micron depth. Here, the two data sets deviate markedly, indicating that there are a high proportion of zero KAM values present. The effect of including the zeros (green points) is to cause the KAM to reach a peak at about 25 micron depth with points nearer the surface showing lower KAM values as the proportion of zero KAM points increases. If zeros are excluded (black points), the KAM continues to rise as the surface approaches but it is worth noting that the high proportion of zero points excluded means that the average KAM value for a scan line close to the surface may only be based on a handful of valid points. However, these considerations do not detract from the determination of the maximum depth of the deformation. Finally, the raw data plotted in Figure 9 shows peaks at 200 and 250micron depth. These originate from the MnS trails that can be seen as high KAM areas at these positions in the KAM image in Figure 8. As any patterns from MnS would not be well indexed by a set up for solving ferritic EBSD patterns, these will exhibit poor CI values which result in them being excluded from the processed datasets, hence minimising the anomalous peaks.

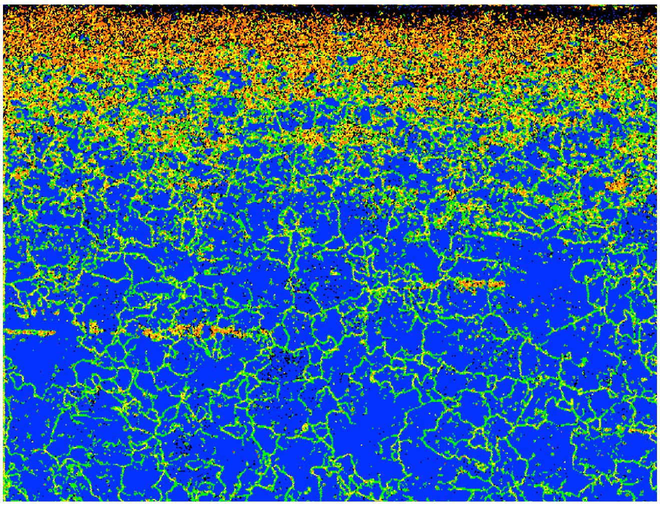


Figure 8 Large Area KAM Map. 500x400μm

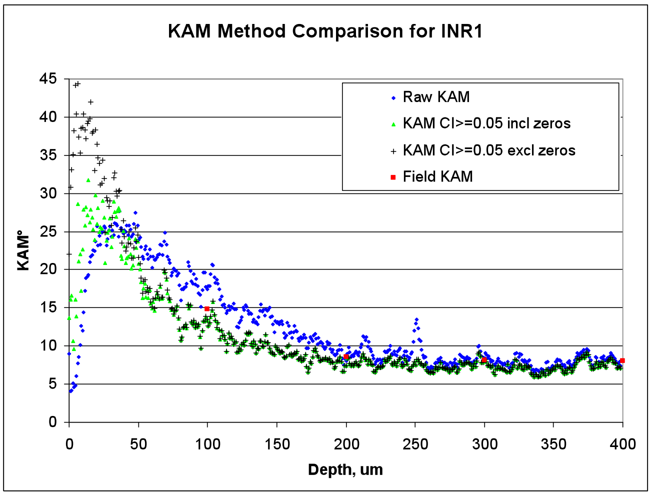


Figure 9 KAM Method Comparison

4 Influence of Rail Grade on Microstructural Deformation

4.1 EBSD "KAM" Analysis of Unused Rail Samples

Running steel wheels on steel rails leads to degradation of both mating surfaces. Although, the change in rail profile and the appearance of rolling contact fatigue cracks are visibly apparent, the magnitude of the strain damage accumulated within the microstructure and how this is affected by the grade of rail steel is not well understood. The use of EBSD techniques has provided a basis of assessing this damage and has been used to study the microstructures in both untrafficked (unused) and trafficked rails as well as those tested under laboratory conditions. The results for untrafficked rails, shown in Figure 10 below, serve as a benchmark against which the accumulated damage in trafficked and laboratory tested samples of the various rail grades can be compared.

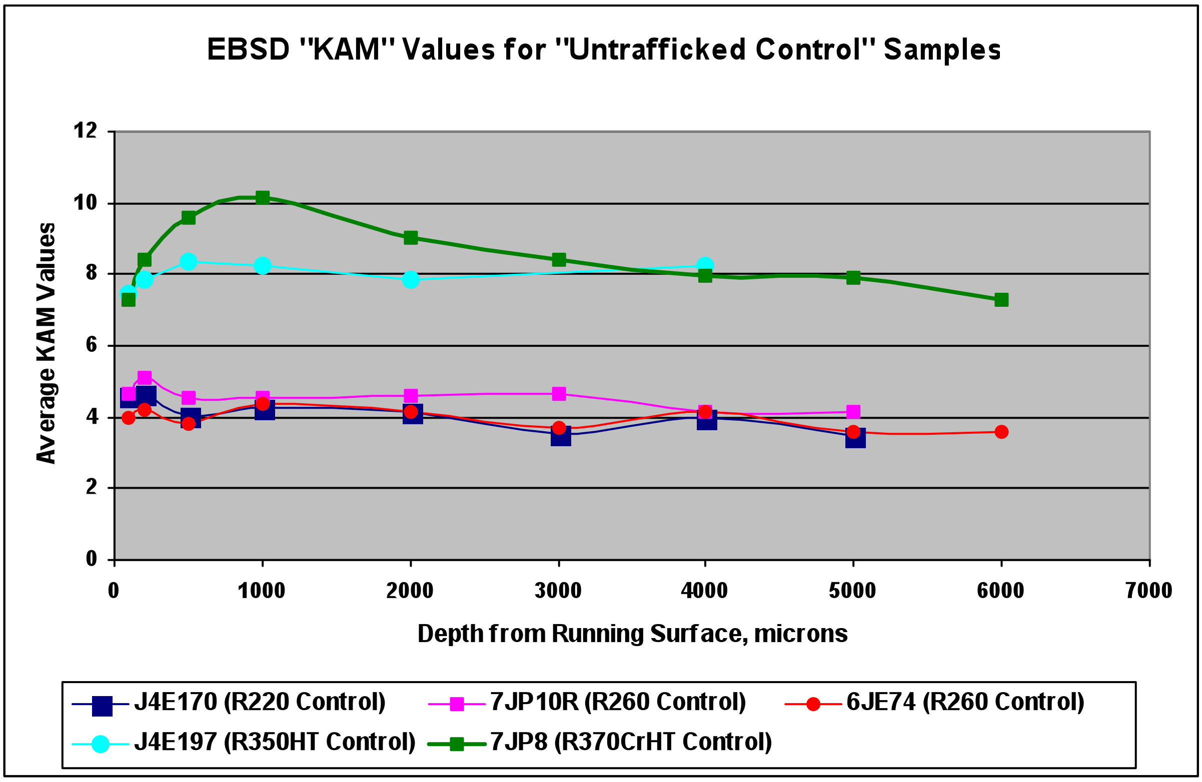


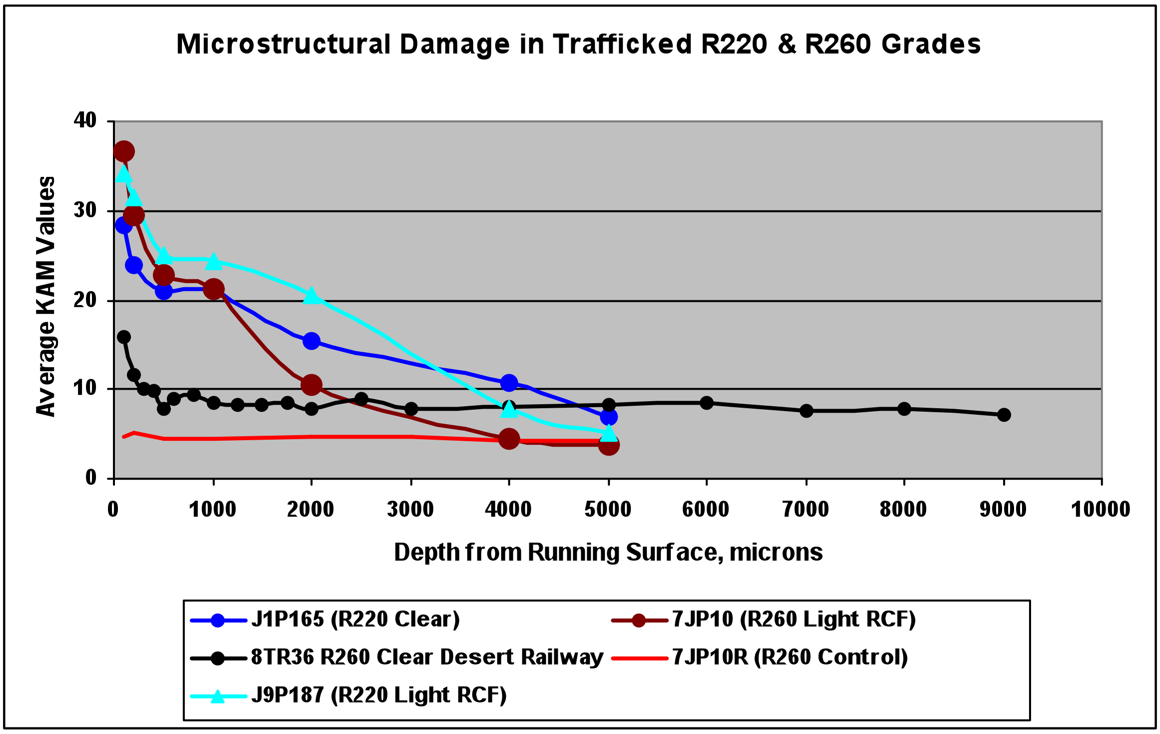
Figure 10 EBSD "KAM" Values for "Untrafficked Control" Samples of Various Grades

The hot rolling process, finish rolling temperature, and the subsequent cooling rates are the processing parameters governing the prior austenite grain size and the room temperature pearlitic microstructure. These are very similar for both Grades R220 and R260 and are also similar between the different manufacturers of these rail grades. Consequently, the similarity of observed "KAM" values is not surprising. Further confidence in the ability of EBSD "KAM" technique to provide a measure of microstructural deformation comes from the consistency in the "KAM" values in the unused control samples of all grades for the full depths examined. The recrystallisation and the relatively high temperature transformation to a pearlitic microstructure are expected to give a uniform and low strain structure.

The second important finding is the higher "KAM" values for the heat treated grades, R350HT and R370CrHT. This is a reflection of the finer grain and pearlite colony sizes that increases the measured misorientation of a given point compared to its six equidistant neighbours. Also, the slight increase in the "KAM" value immediately below the running surface followed by a gradual decrease particularly in R370CrHT grade is thought to be a reflection of the very fine grain size developed as a result of the off-line heat treatment process. It should be noted that there is normal misalignment in all but single crystalline material that gives rise to an inherent "background noise" in the measurement that increases in finer grained materials.

4.2 EBSD "KAM" Analysis of Trafficked Rail Samples

It is apparent from the sample matrix shown in Table 1 that there are significant differences in the track characteristics and the volume of traffic carried at the locations from which the samples have been obtained. Although it would have been useful to have examined controlled samples from locations with similar track and traffic type characteristics but with different tonnage carried, this is not practical and would not have excluded the influence of the random variations of the wheel profiles, and hence the stress conditions, experienced by the samples. Nevertheless, since the deformed state of the microstructure is a direct and forensic evidence of the microstructural damage accumulated due to the passing traffic, it is plausible to examine samples from various sites and varying degrees of visible RCF damage to establish the influence of rail grades. These assessments for the various rail steel grades with varying degrees of visible RCF damage are shown in Figures 11 and 12 as a function of the depth from the running surface.



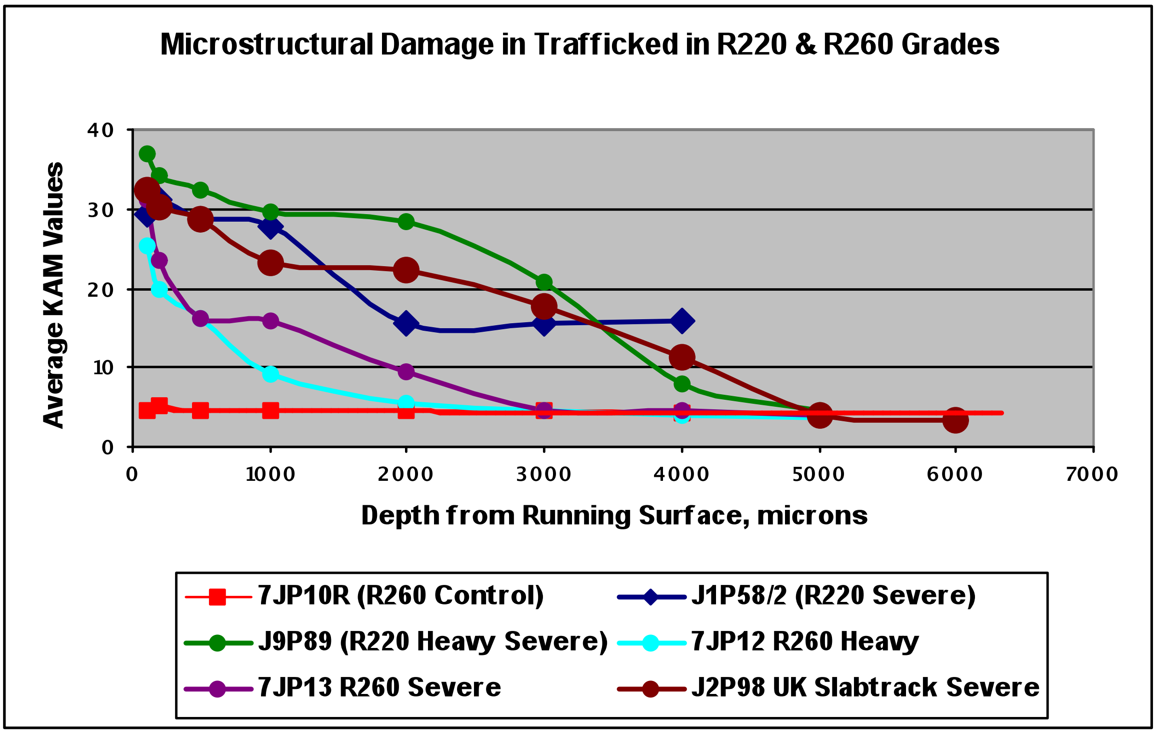


Figure 11 a & b EBSD KAM Values as a Function of Depth for As Rolled Rail Grades R220 and R260

In general, the KAM values are maximum at the surface, show a short plateau at ~1mm depth followed by a gradual decrease to the level observed in the untrafficked control samples. The maximum KAM value at the surface is likely to be more influenced by the surface stresses and hence the contact patch conditions with particular reference to lateral loading. Consequently comparison of this value for the different rail grades would need to be done on samples experiencing similar loading conditions. The shape of the KAM curves could be of interest with reference to the sub-surface stresses generated, the increase in microstructural deformation resulting from sliding of RCF crack faces, and the magnitude of traffic carried. This aspect requires further controlled investigation and is the subject of a separate Corus sponsored research project at University of Birmingham. However, the key finding of interest to the railways is the depth to which the microstructural deformation extends. In this respect, it is noteworthy that despite different sample locations and severity of RCF cracks, the depth of microstructural damage in Grade R220 appears to be ~5mm. However in the case of Grade R260, the observed depth of microstructural damage was in the range of 3mm to 5mm. Interestingly, the light and severe RCF samples from a single location in DB track had microstructural damage to depths of 5mm and 3mm respectively. Similarly the UK sample from a slabtrack railway line exhibiting severe RCF cracks had microstructural damage to a depth of 5mm. These differences are likely to be a reflection of differences in local track conditions or the influence of traffic differences.

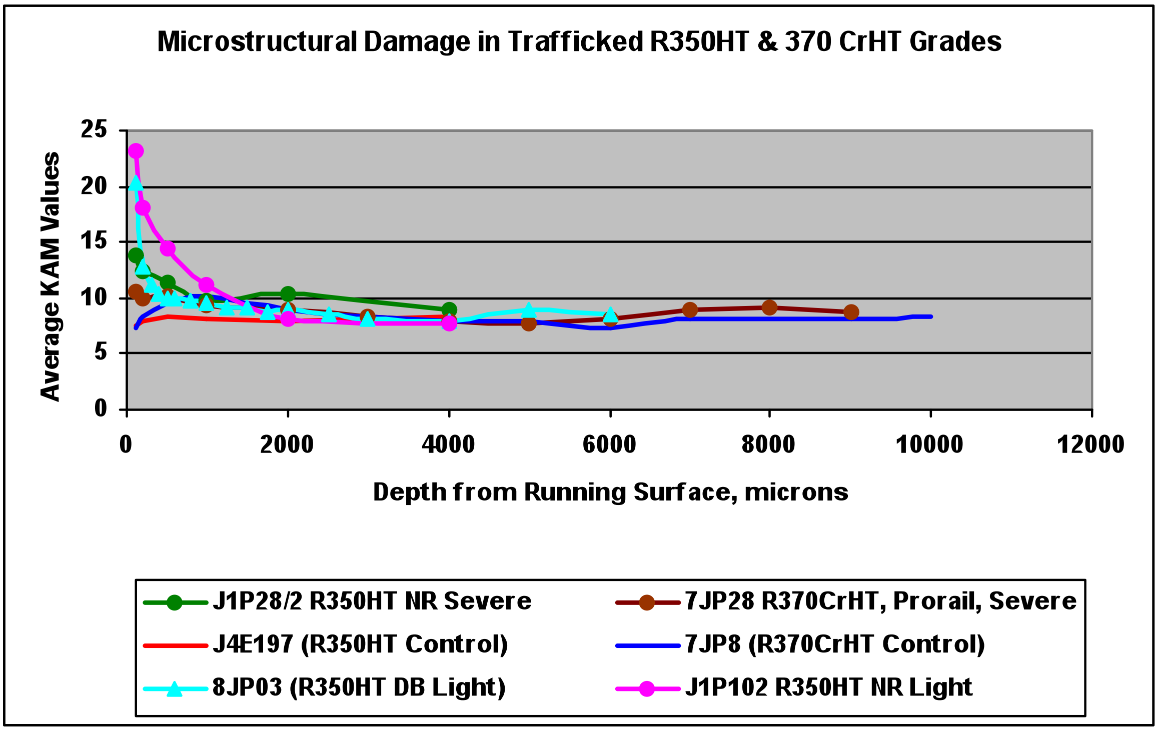


Figure 12 EBSD KAM Values as a Function of Depth for Rail Grades R350HT & R370CrHT

In the case of the heat treated rail grades (R350HT and R370CrHT), the depth of microstructural deformation is considerably shallower with a range of 2mm to 4mm for R350HT and 1mm to 2mm for R370CrHT as is evident from Figure 12 above. In the case of the samples with severe RCF cracks, it is possible that the lower surface values of KAM are a result of grinding undertaken in the recent past before the samples were removed.

In summary, examination of the trafficked rail samples has demonstrated that objective assessment of microstructural deformation can be undertaken using the EBSD procedure described. The data clearly show the differences between the various grades of rail steels with particular reference to the depth of microstructural deformation/damage:

Table 2 Maximum Depth of Microstructural Deformation for Various Rail Grades

Rail Grade	Maximum Depth of Microstructural Deformation, mm
R220	5+
R260	3 to 5
R350HT	2 to 4
R370CrHT	1 to 2
R400HT	Track samples not available

The above results indicate that the magnitude of grinding required to reveal the original undeformed (undamaged) microstructure decreases with increasing hardness of the rail and since the harder grades are also associated with longer periods to initiation of RCF, clear economic and LCC benefits can be realised through the use of harder grades. However, it should also be emphasized that the samples of both heat treated grades (R350HT and R370CrHT) examined in this study exhibited severe RCF cracks with vertical depths of ~5mm but the measured microstructural deformation was much shallower than the depth of the cracks.

4.3 EBSD “KAM” Analysis of Samples from Laboratory Tests

A key objective of SP4 of the Innotrack project was to assess critically the various laboratory tests available for the evaluation of wear and rolling contact fatigue of various rail grades and the results are reported in a separate document. The work reported in this document is supporting investigation to assess the microstructural deformation resulting from the various laboratory tests[3-8].

4.3.1 Twin Disc Test Samples

The matrix covered by SUROS twin disc (47mm diameter[8]) laboratory tests was:

<u>Rail Grade</u>		<u>Cycles</u>
R260		5000 dry cycles
R350HT	X	15000 dry cycles
R370CrHT		5000 dry + 5000 wet cycles
R400HT		20000 wet cycles

The majority of the samples tested on the SUROS machine were also examined using the EBSD technique. It became apparent that the depth of microstructural deformation was very shallow and the assessment technique had to be modified as described in Section 4.2. The influence of the number of dry and wet cycles was very similar for all the rail steel grades examined as is evident from the example of the R260 and R370CrHT grades shown in Figures 13 and 14 respectively.

For R260 Grade, the KAM value of the control sample (i.e. the undamaged microstructure) was reached at a depth of ~600 microns regardless of the number of dry and/or wet cycles. The microstructural damage (KAM value) under the fully wet testing regime (20000 wet cycles) was slightly lower up to a depth of ~200 microns beyond which the magnitude of damage was similar to the other testing regimes for this grade.

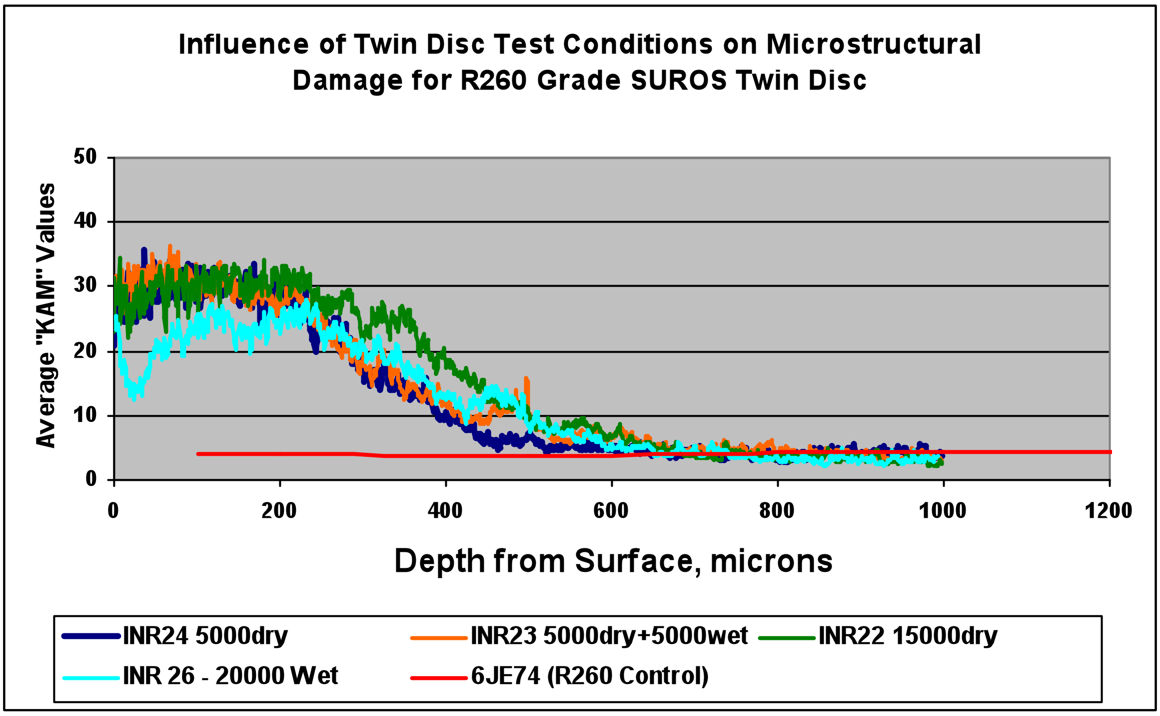


Figure 13 Influence of SUROS Test Conditions on Microstructural Damage in R260 Grade

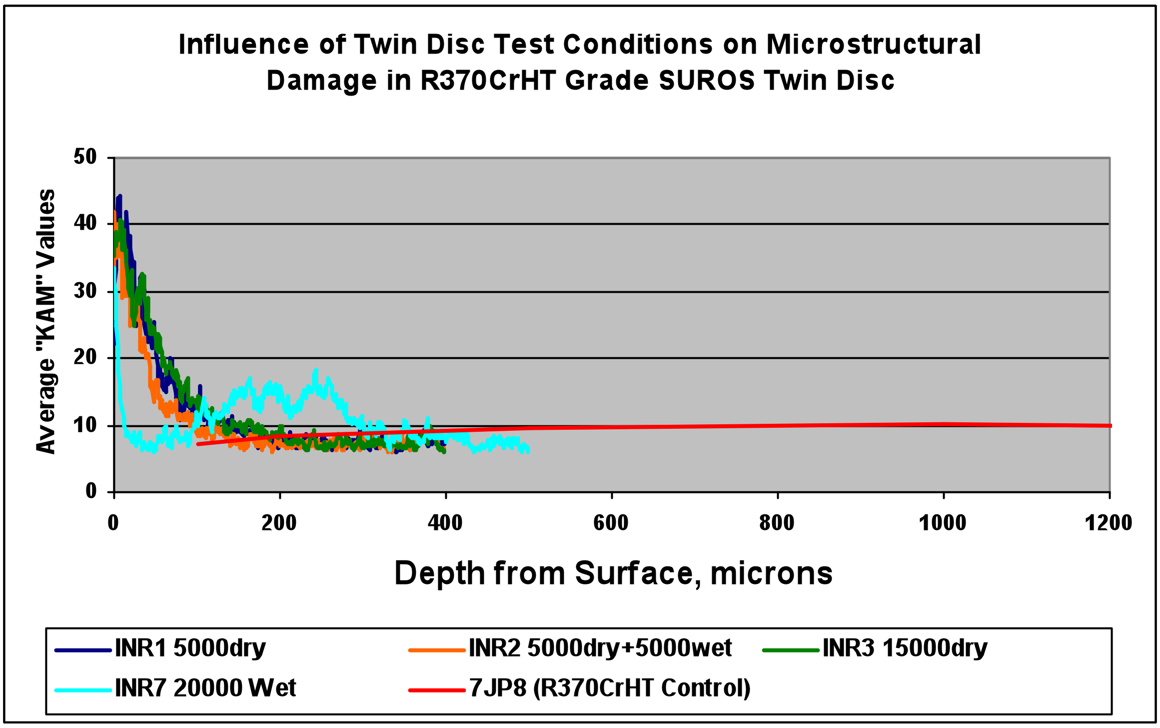


Figure 14 Influence of SUROS Test Conditions on Microstructural Damage in R370CrHT Grade

In the case of R370CrHT Grade, the KAM value of the control sample (i.e. the undamaged microstructure) was reached at a depth of just ~200 microns for all testing regimes except for the 20000 wet cycles, in which case the control KAM value was reached at just ~25 microns followed by a slight increase before returning to the level of the control sample. This behaviour was also observed in samples of other grades tested under the regime of 20000 wet cycles. Although the magnitude of increase in the KAM values at intermediate depths was small to suggest any significant accumulation of damage, the significance of this pattern of microstructural deformation may lie in the influence of the very low levels of friction in the wet cycle tests.

The degree of susceptibility to microstructural deformation of the various rail grades, as adjudged by the SUROS twin disc test is shown in Figure 15. Compared to the depths of microstructural deformation seen in trafficked samples taken out of track (Table 2), those associated with the SUROS twin disc tests are significantly shallower with a value of just 600 microns compared to up to 5mm observed in the track Grade 260 samples.

Hence, there was a need to examine the testing conditions employed in the SUROS tests in terms of the number of dry cycles prior to the use of water lubrication. Consequently, similar EBSD analyses were undertaken on a limited number of samples from the twin disc tests undertaken on an Amsler facility within the research laboratories of Corus. The key operational difference between the two twin disc test facilities (SUROS & Corus) was the use of just 250 dry cycles in the Corus tests compared to a minimum of 5000 dry cycles in the SUROS tests undertaken within this programme. The Corus tests were performed at contact pressure of 950 MPa with a 5% slip compared to 1500 MPa with a 1% slip used on the SUROS tests. A further difference was that the Corus tests were continued until visible signs of the initiation of RCF cracks were present whereas the SUROS tests were undertaken for a fixed number of cycles, 5000 dry plus 5000 wet cycles. Thus the Corus tests were continued for 50000 cycles for the R260 grade and for ~110,000 cycles for the R370CrHT grade sample. The results of EBSD analysis for both test techniques are shown in Figure 16.

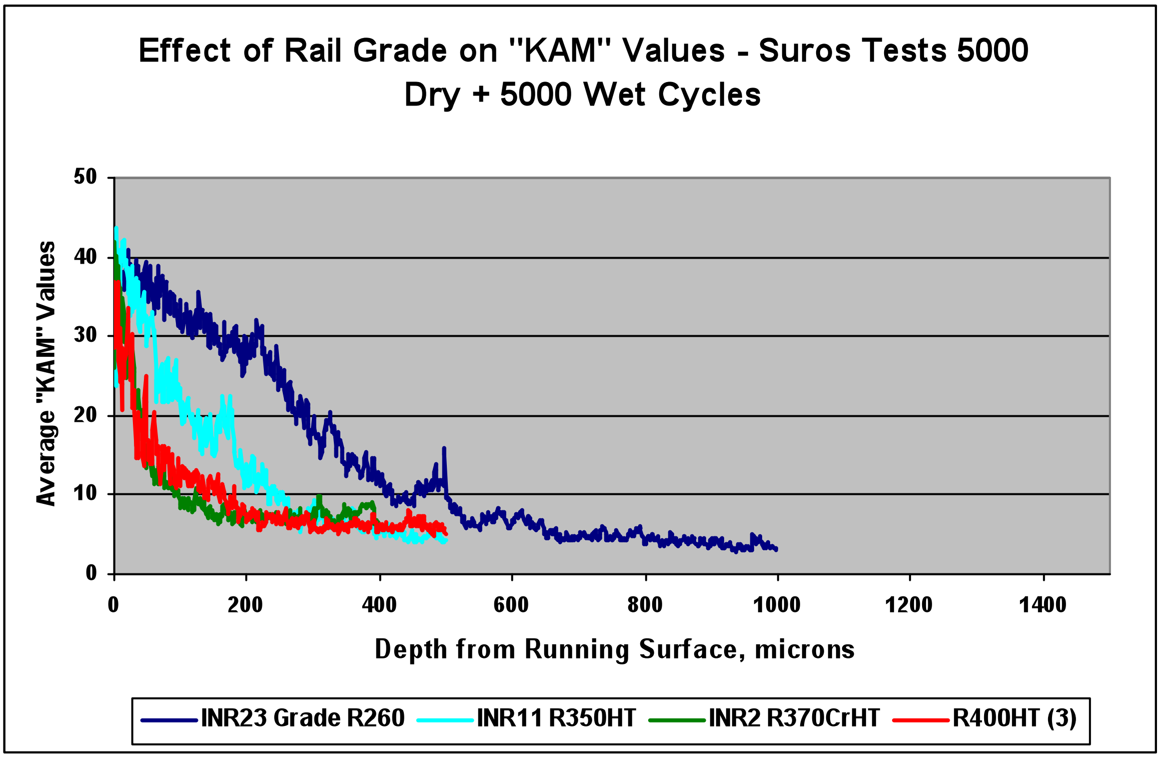


Figure 15 Effect of Rail Steel Grade on Microstructural Deformation in SUROS Twin Disc Tests

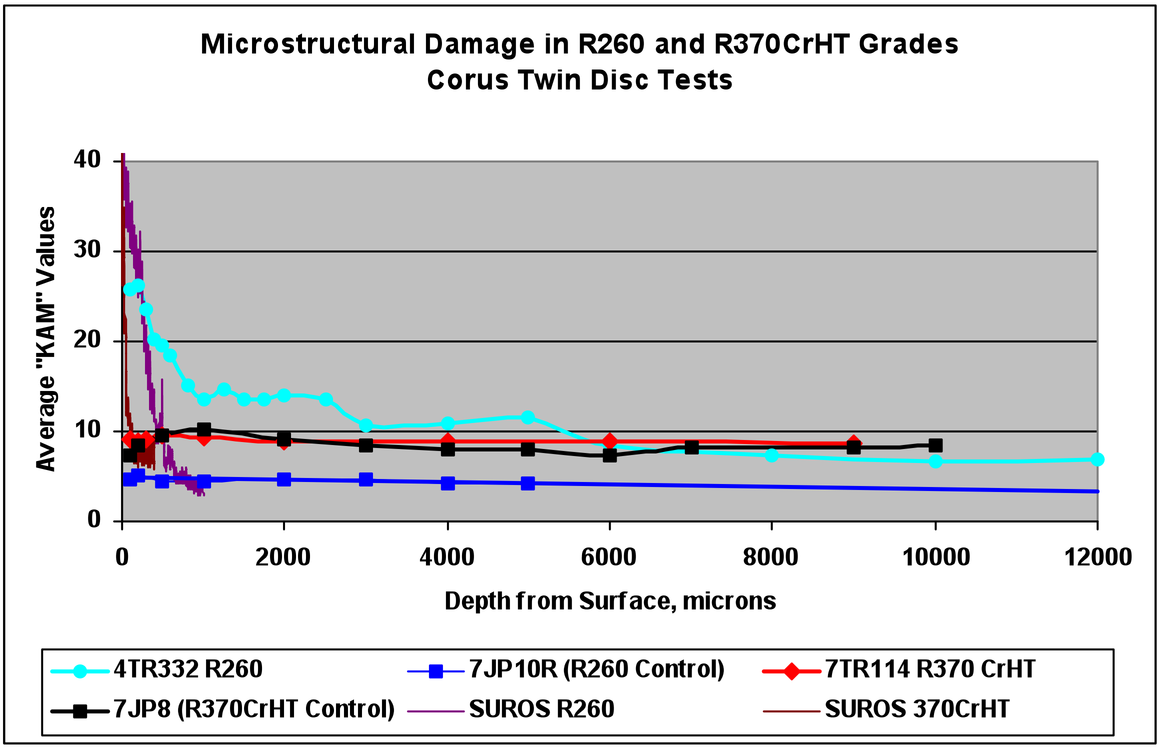


Figure 16 Effect of Rail Steel Grade on Microstructural Deformation in Corus Twin Disc Tests

Although Corus has undertaken over 900 tests in a range of steel grades in the past, EBSD analysis was done only on one sample each of Grade R260 and R370CrHT. The differences in the depths of microstructural deformation observed in the samples from the two test regimes are immediately apparent. For both rail grade samples, the Corus tests exhibited a much lower KAM value at the surface than those in the SUROS tests. This is a likely effect of the lower contact pressure and the reduced number of dry cycles in the Corus tests. In the case of Grade R260, the rate of decay in the magnitude of microstructural deformation is also more gradual in the Corus tests with the value of the control sample not being reached even at a depth of 12mm compared to just 1mm in the case of SUROS tests. In the case of R370CrHT grade samples, the rate of decay in microstructural deformation is also different for the two twin disc testing regimes but that from the Corus test is difficult to quantify in view of the very limited microstructural deformation even at the surface. Nevertheless the results from the Corus facility closely match those from the control sample at all depths examined. Consequently, it is reasonable to conclude that twin disc tests can be used to simulate microstructural deformation experienced by rails in track but controlled evaluation is necessary to establish the contact pressures, the magnitude of slip, and the number of initial dry cycles. Furthermore, it should also be recognised that the contact conditions in twin disc tests are unlikely to be able to simulate the microstructural deformation experienced at the gauge corner or the side of head of rails in track.

4.3.2 DB Full Scale Wear and RCF Test Rigs

DB test Rigs ‘A’ and ‘C’ have been used to simulate the contact conditions prevalent in track that result in the formation of RCF cracks. The details of the test rigs and the conditions employed are detailed in a separate report[6]. As detailed in Table 1b, one sample from Test Rig ‘A’ and a further sample from Test Rig ‘C’ were received for assessment of microstructural deformation employing the developed EBSD technique. In the case of the sample from Test Rig ‘A’, samples were taken from the centre of the head and from the gauge corner. The results are summarised in Figure 17 below.

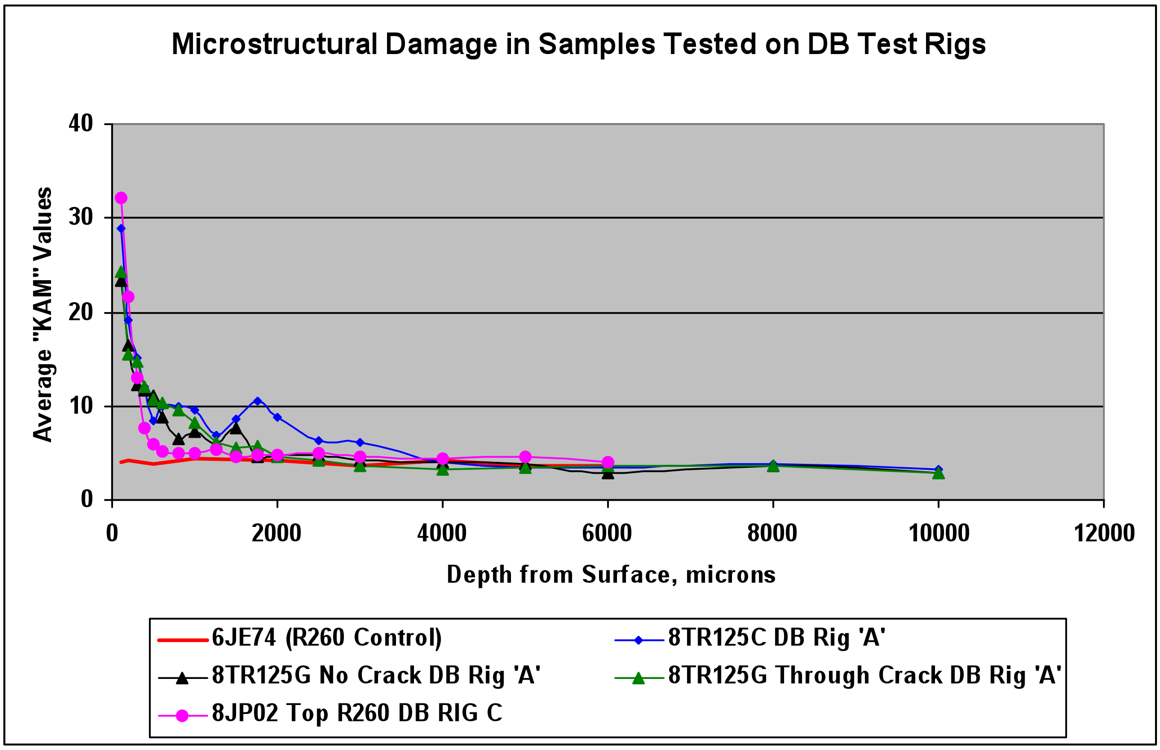


Figure 17 **Microstructural Deformation in Samples from DB Test Rigs 'A' and 'C'**

The comparison of the top/centre samples from Rig 'A' and 'C' reveals the similarity of the highest KAM values near the surface and the very rapid rate of decay in this parameter to a depth of 500 microns. Beyond this point the Rig 'C' sample continues to show reduced microstructural deformation to a depth of in between 1mm and 2mm when it reaches a similar level to that recorded for the controlled untrafficked sample. In contrast, although the rate of decrease in microstructural deformation in the sample from rig 'A' has decreased significantly, the value matching the control sample is not reached till ~4mm. This value is closer to that observed in samples from commercial track but it should be noted that this sample had been tested at various loading conditions accumulating between 300 to 400 MGT in over 8 years of testing.

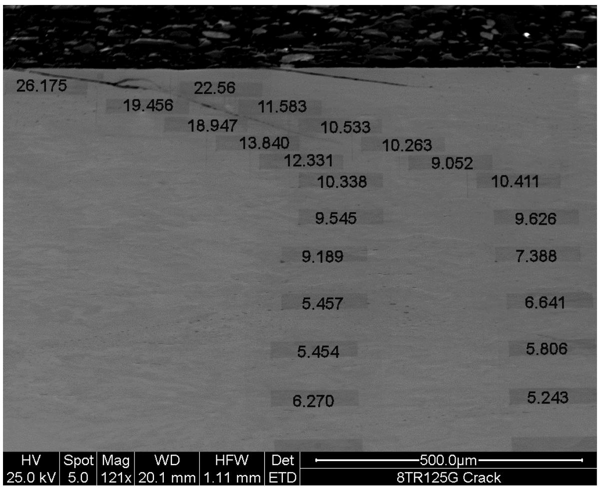


Figure 18 Microstructural Deformation Away from and Within a RCF Crack Area (DB Test Rigs 'A' – 8TR125G))

In the case of the gauge corner sample from Test Rig 'A', the EBSD analysis was undertaken in areas away from and within an observed RCF crack as shown in Figure 18. It is interesting to note the differences in the KAM value on either side of the crack that indicates the influence of the sliding of crack faces and hence greater microstructural deformation. However, the magnitude of deformation becomes very similar away from the crack.

A comparison of the magnitude of microstructural deformation in the various laboratory tests with those observed in samples from commercial track is made in a later section.

4.3.3 vas Roller Rig Tests

Details of the vas Roller Rig and the test conditions employed are given and discussed in a separate report[7]. The following samples were subjected to the assessment of microstructural deformation using the developed EBSD technique. The results are presented in Figures 19 to 21 for the various rail grades.

Table 3 vas Roller Rig Samples for EBSD Analysis			
QA Code	**Sample Type**	**Rail Grade**	**Comments**
9TR109C	VAS RIG	R260	Gauge corner
9TR110C	VAS RIG	R350HT	
9TR111C	VAS RIG	R370CrHT	
9TR109T	VAS RIG	R260	Top of rail
9TR110T	VAS RIG	R350HT	
9TR111T	VAS RIG	R370CrHT	
9TR112T	VAS RIG	R400HT	

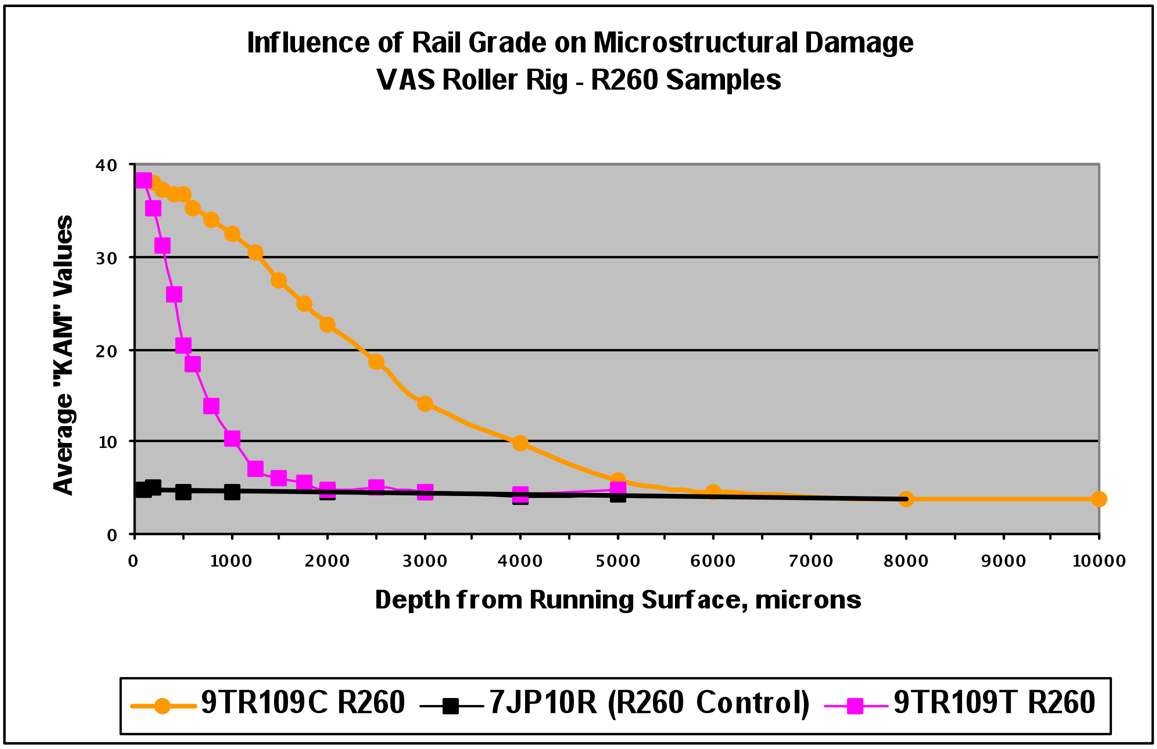


Figure 19 **Microstructural Deformation in R260 Grade in vas Roller Rig Tests**

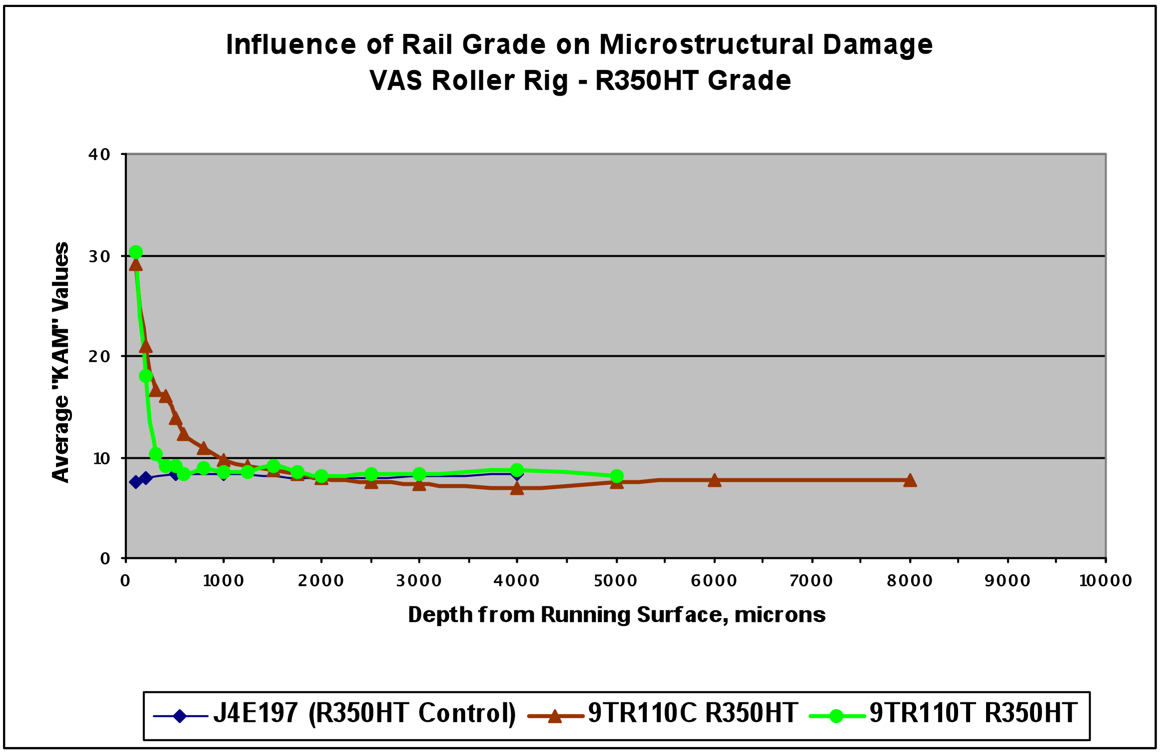


Figure 20 Microstructural Deformation in R350HT Grade in vas Roller Rig Tests

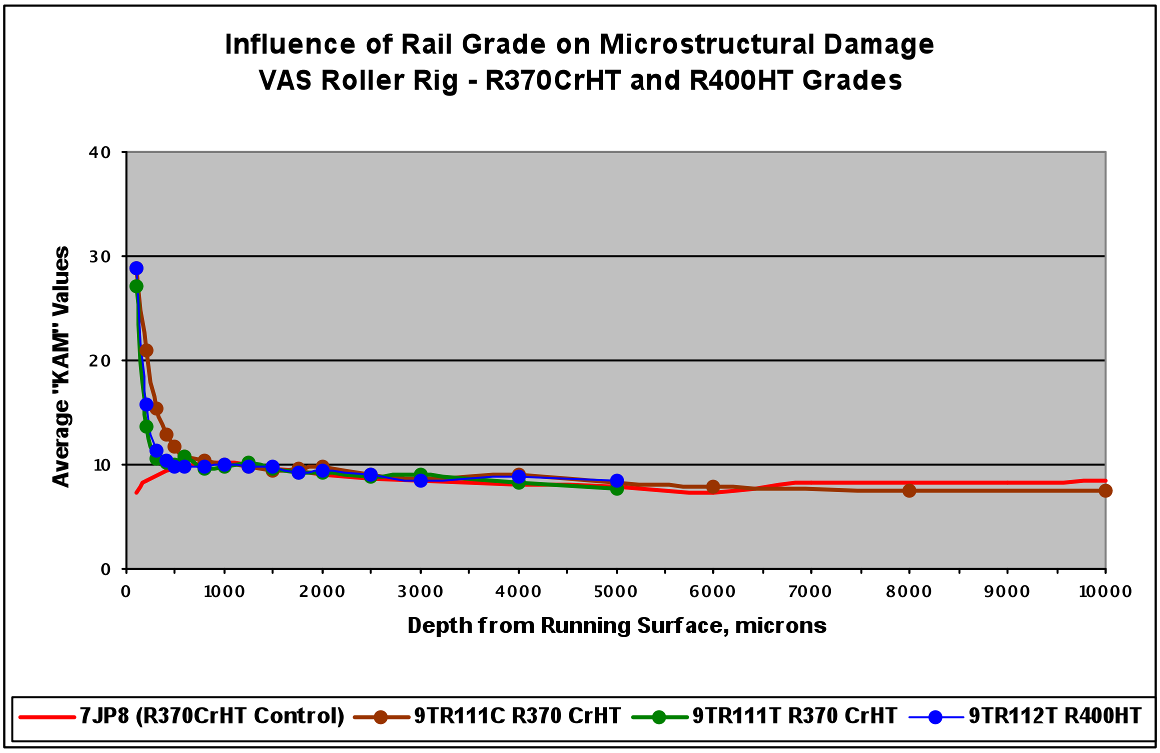


Figure 21 Microstructural Deformation in R370CrHT & R400HT Grades in vas Roller Rig Tests

The above results are summarised in Table 4 below for the purposes of comparison of the behaviour of the various rail grades:

Table 4 EBSD Analysis Data for Samples from vas Roller Rig

Rail Grade	Max KAM value at Surface		Depth of Microstructural Deformation, mm	
	Top of Rail Head	Gauge Corner	Top of Rail Head	Gauge Corner
R260	38	38	2	6
R350HT	29	30	0.5	2
R370CrHT	29	27	0.6	0.8
R400HT	29	NA	0.6	NA

It is apparent that the microstructural deformation close to the surface is very similar for all grades or, as explained in Section 2, the EBSD analysis technique is not discriminating enough due to non-indexable or indexed orientation points with low confidence in the solution. However, in terms of the maximum depth of microstructural deformation, there are significant differences between the results for the top of the rail head and the gauge corner suggesting that the rail wheel contact was focussed on the gauge corner that is more relevant to curved tracks susceptible to RCF. It is recommended that the contact conditions for both these locations be compared to support the observed differences in microstructural deformation.

4.4 Comparison of EBSD Analysis Data for Trafficked & Laboratory Tests

A second objective of the programme was to ascertain whether the microstructural deformation measured for the various laboratory tests were a reliable representation of that observed in the samples taken out of track. The graphical results are apparent in Figures 22a to 22c below for the various rail grades and a brief summary of the maximum "KAM" (deformation) value at the surface and the maximum depth of deformation are summarised in Table 5.

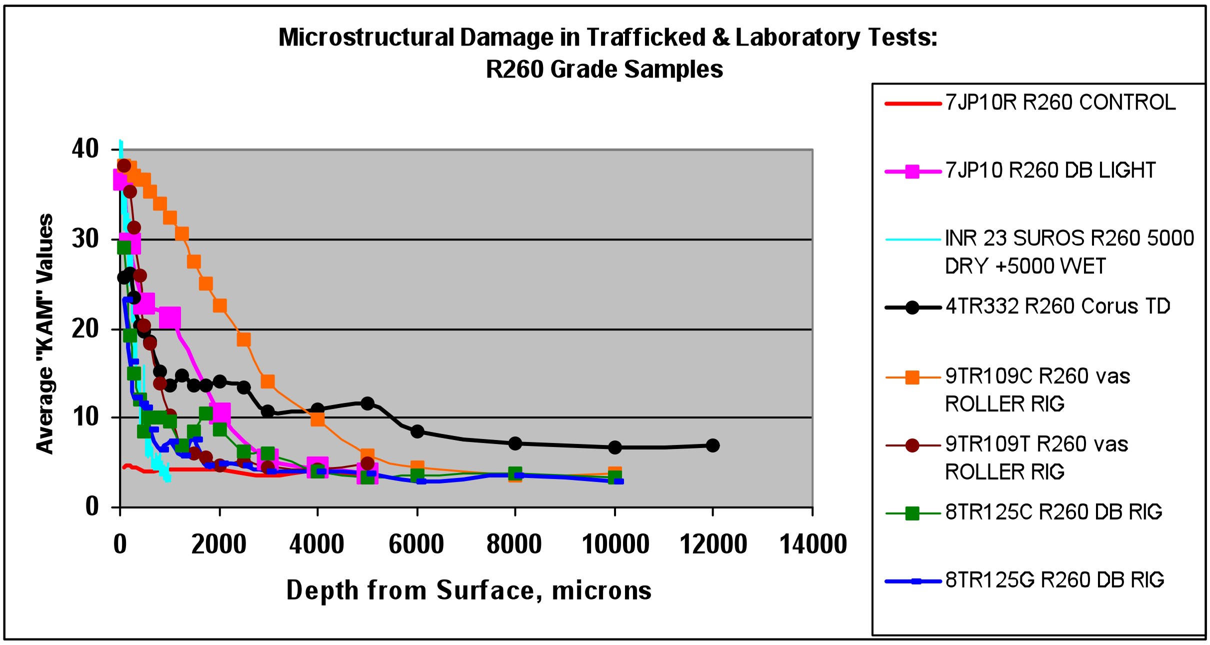


Figure 22a Comparison of Microstructural Deformation in Trafficked & Laboratory Tests; R260

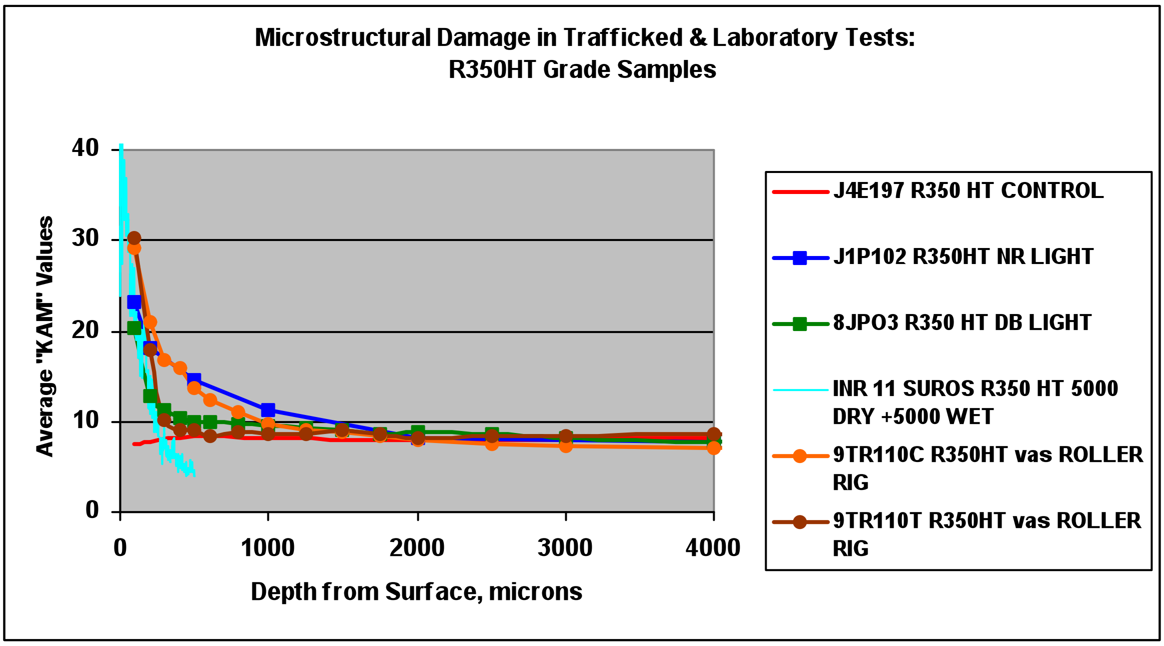


Figure 22b Comparison of Microstructural Deformation in Trafficked & Laboratory Tests; R350HT

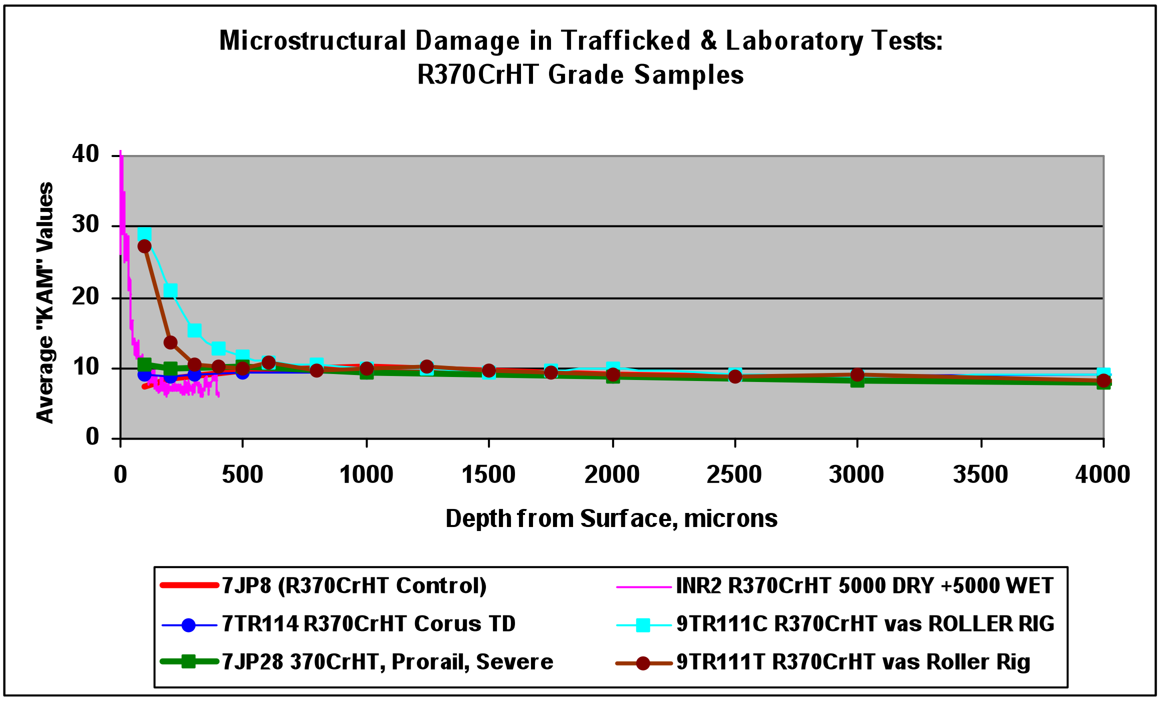


Figure 22c Comparison of Microstructural Deformation in Trafficked & Laboratory Tests; R370CrHT

It should again be emphasized that the microstructure very close to the surface is very heavily deformed and does not permit reliable indexation of the degree of misorientation and since focus has to be on the depth to which the microstructural deformation extends, more emphasis has been given to establishing a close match of this parameter between the various laboratory tests and the trafficked track samples. However, the lack of detailed pedigree of trafficked samples could also be a contributory factor to the observed differences with the laboratory tested samples.

Table 5 Comparison of EBSD Analysis Data

Track/Lab Tests	**Rail Grades**					
	R260		**R350HT**		**R370CrHT**	
	Max KAM	Depth of Def.	Max KAM	Depth of Def.	Max KAM	Depth of Def.
Track Trafficked Top of head Sample	37	5	20-23	2-3	9-10	1
SUROS 5000 dry + wet	42	0.8	26	0.3	42	0.1
Corus Twin Disc	26	>6	Not undertaken		9	1
DB Rig A	28	1.5	Not undertaken			
DB Rig C	23	1				
vas Roller Rig Top of head	38	2	29	0.5	29	0.5
vas Roller Rig Gauge corner	38	6	30	2	27	0.8

<u>**Twin Disc Tests:**</u> It is apparent that for all rail grades tested, the SUROS twin disc tests reveal a much shallower depth of damage than other laboratory tests or the trafficked samples. This is likely to be a result of the unusually large number of dry cycles leading to wearing off of some of the “damaged” layer. However, the use of up to 20,000 wet cycles alone (Figure 13) also resulted in very shallow depth of damage because of the very low level of friction. This aspect requires further investigation with reference to the contact patch conditions

In contrast, the Corus Twin Disc test for Grade R260 revealed a plateau in the level of KAM value at a depth of ~6mm but did not get down to the level observed in the control sample. The reasons for why the Control sample KAM value was not reached even to a depth of 12mm is not clear but that the rate of decay to this plateau level is very similar is considered encouraging.

For the R370CrHT rail grade, there is close correlation between a trafficked sample with severe RCF cracks and the Corus twin disk result but not with the results from the SUROS tests. Further samples from both track and laboratory tests need to be examined to confirm these results particularly with respect to the absence of high KAM values even close to the surface.

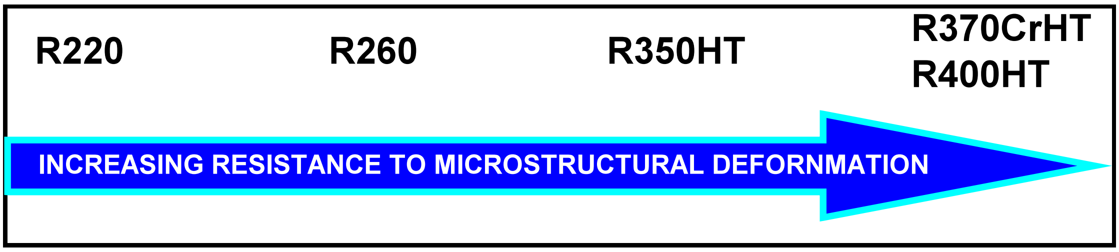
For both sets of twin disc tests, it is recommended that optimisation of the test conditions is undertaken with particular reference to the number of dry cycles, the magnitude of slip, and the type, timing and magnitude of lubrication. Comparison of the depth of microstructural deformation in these tests with that found in trafficked samples of known pedigree should form the judgement criterion for optimisation of the test conditions. Although the simple contact conditions of this test configuration is acknowledged, its simplicity and cost effective testing procedures make it an attractive proposition. For this purpose, it is necessary to examine the microstructural deformation in a matrix of trafficked samples with known pedigree to establish the track characteristics for which the microstructural deformation can be reasonably well reproduced in this simple test.

<u>**DB Test Rigs ‘A’ and ‘C’:**</u> The use of these two test techniques was restricted to R260 grade only and despite the significant differences between the two test rigs and the volume of simulated traffic carried, the characteristics of the measured microstructural deformation is very similar (Figure 22a and Table 5). However, when compared to trafficked sample from the DB network, the much shallower depth of microstructural deformation was apparent in the samples from the two test rigs. Furthermore, unlike the SUROS tests, there was no comparable information on other rail grades, which could be used to examine the comparative ranking order of the resistance to microstructural deformation of the various rail grades. However, the complexity of sample

preparation makes a programme of work involving a matrix of rail grades, contact, and loading conditions impractical.

vas Roller Rig: The comprehensive programme of testing covering the full range of rail steels has permitted a closer examination of the effect of rail grade on microstructural deformation under controlled rail-wheel contact conditions. It is apparent from Figures 22a to 22C and the summary data in Table 5 that the microstructural deformation measured from the gauge corner of the test samples reflects good correlation with trafficked samples. However, for all grades examined, the microstructural deformation from the top of the head locations was appreciably less and achieved the value of the control sample at a much shallower depths than those in trafficked rails of the corresponding grade. It is also interesting to note that in the case of R350HT, the microstructural deformation in the corner sample resembled the trafficked sample from Network Rail track while the top of head sample closely resembled the trafficked rail from DB track. In contrast the deformation in both sample positions for Grade R370CrHT, was much greater than that observed in Prorail track.

The clear conclusion is that microstructural deformation reflects the specific loading conditions and that the optimum selection of rail grades for the wide variety of loading conditions that exist on any railway network should be based on the performance of the rail grades under very closely controlled test conditions as undertaken in this programme. Although the microstructural assessment undertaken in this programme could have covered the full matrix of grades and loading conditions, the consensus that has resulted from the trends observed in each of the laboratory tests leads to the conclusion:



The implication of the increased resistance to microstructural deformation also needs to be put into the context of the rail wheel contact conditions and the practicality of track maintenance. It is in this context that the increased resistance to microstructural deformation offers several advantages;

1. Maintaining the crown profile for longer periods to ensure the desired rail-wheel contact
2. Increased proof strength to resist plastic deformation in a railway network designed for higher speed passenger traffic and increasingly being asked to carry more freight traffic at lower speeds
3. Increased resistance to the initiation of rolling contact fatigue as demonstrated by the laboratory tests and the degradation models based on a wide range of track trials
4. The much lower depth of microstructural “damage” that can potentially be removed more effectively through single pass grinding at longer intervals.

The above knowledge of the resistance to microstructural deformation has been combined with rail degradation algorithms derived from extensive track trials to arrive at the “D4.1.5 Guidelines for Rail Grade Selection”

5 Conclusions

Electron Back Scatter Diffraction technique has been applied in a novel manner for the assessment of microstructural misorientation that results from the stresses imposed by rail wheel contact. The key conclusions from the work reported are:

1. Using control samples of **UNUSED** as-manufactured rail, it has been shown that the degree of misorientation measured by EBSD technique is minimal from the surface to the measured maximum depth of 5mm. Since hot rolled rails undergo high temperature static recrystallisation immediately after rolling, the minimal microstructural misorientation measured by the developed EBSD technique demonstrates the validity of the technique. In the case of **UNUSED** as-manufactured heat treated rails, the degree of the measured microstructural deformation ("damage" relative to unstrained microstructure) is slightly higher than that for as rolled non-heat treated grades, which is probably a reflection of the finer pearlitic microstructure. Consequently, EBSD analysis has been shown to be a credible technique to determine the magnitude of microstructural misorientation and its use for assessing the magnitude of "microstructural damage" from the passage of traffic. The proposed technique is the only direct and objective measure of accumulated "damage" imparted by wheel-rail interaction and is far more discriminating than the currently used technique of microhardness measurements.
2. The most important finding of this work is the determination of the depth at which the microstructural misorientation in trafficked samples reaches that of unused rail i.e. the depth of the "damaged layer". The values indicate a decreasing depth of "damaged layer" with increasing hardness of the rail with R370CrHT and R400HT grade rails showing "damage" depths of <1mm. Clearly, the very limited depth of the "damaged layer" in the premium harder rail steel grades suggests that the "damaged layer" could be removed by light grinding to expose undeformed ("undamaged") microstructure.
3. The assessment of samples from twin disk tests, employing an unusually large number (5000) of dry cycles, has also shown a decrease in depth of "damaged layer" with increasing rail hardness. However the absolute magnitude of depths were significantly less than the corresponding figures for trafficked samples. This has been attributed to the removal of material as a result of the high wear during the dry cycles. It has also be suggested that the shallower depth of the deformed/stressed layer may be a reflection of the contact geometry. However, a reduction in the number of dry cycles from 5000 to just 250 in the Corus Twin Disc tests has given depths of "damaged layer" that are similar to those observed in trafficked samples and hence provide confidence in this simple test to provide reliable comparative properties for the various rail grades.
4. The microstructural deformation measured from the gauge corner of the test samples from the roller rig at vas reflects good correlation with trafficked samples. However, for all grades examined, the microstructural deformation from the top of the head locations was appreciably less and achieved the value of the control sample at a much shallower depths than those in trafficked rails of the corresponding grade. This is probably a result to the specific contact and resulting stress condition.
5. Based on the assessment to date, it is concluded that microstructural deformation reflects the specific loading conditions and that the optimum selection of rail grades for the wide variety of loading conditions that exist on any railway network should be based on the performance of the rail grades under very closely controlled test conditions as undertaken in this programme. The rail grades in order of increasing resistance to microstructural deformation are: R220, R260, R350HT, with the highest resistance being provided by R370CrHT and R400HT. The advantages that could be realised in the appropriate track locations are:
    - Maintaining the desired crown profile for longer periods to ensure the desired rail-wheel contact

- Increased proof strength to resist plastic deformation in a railway network designed for higher speed passenger traffic and increasingly being asked to carry more freight traffic at lower speeds
- Increased resistance to the initiation of rolling contact fatigue as demonstrated by the laboratory tests and the Innotrack developed degradation models for RCF resistance based on a wide range of track trials
- The much lower depth of microstructural "damage" that can potentially be removed more effectively through single pass grinding at longer intervals.

The above knowledge of the resistance to microstructural deformation has been combined with rail degradation algorithms[11] derived from extensive track trials to arrive at the "Guidelines for Rail Grade Selection"[12]

It is recommended that the work be extended to examine the effect of the magnitude of traffic on the depth of the "damaged layer" using controlled samples from track. Further research is also recommended to establish a correlation between the measured KAM values and the accumulated strain.

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