Surface Analysis Forum Newsletter No. 21

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Please tell us more about the work you do so we can plan future meetings and advise manufacturers on the community's requirements

Meeting Report

"Joint" studies in Surface Analysis

British Aerospace, Bristol Wednesday 5th July 1996

The Group was welcomed by Dan Kells, the Director of Sowerby Research Centre.

Dave Dixon (BAe, Bristol) opened the morning session with a talk describing operation

of joint projects at BAe and the benefits accrued. The main reason for BAe's involvement with joint projects is to obtain additional funding and there may be twenty or so running at any one time. In most cases the funds come from the European Commission via one of many schemes to encourage technological development in strategic areas - aerospace being a major one

The EC is not just a "pot of gold", it has very strict conditions and published guidelines for collaborative projects and those proposals submitted must be seen to be well thought out, well planned, well managed and well resourced. Of ~1100 proposals for Brite-Euram funding 20% were rejected due to incorrect presentation, 60% were rejected after consideration and 20% were funded. Progress against milestones must be reported at specified intervals and it is the project chairpersons responsibility to ensure that the contractors know what is expected and when. The EC audits the project and treats the final programme as a contract. Each proposal is assessed for clear, verifiable and realistic technical aims, a significant socio-economic impact, its financial credibility and technical merit. It is imperative that each project has a potential for commercialisation.

Most industrial Brite-Euram projects involve a minimum of 10 man years, spread over 2-4 years and involve at least two countries. The industry gets 50% funding and any universities involved get 100% of their marginal costs. For basic research projects in the 0.5-1 MECU cost range, industry gets 15% of its costs.

The results of a collaborative project are always a compromise. Although it is essential to work within the rules of the EC, the advantages of seeing what other industries do and how they work and the improvement in European scientific cohesion makes these projects very rewarding. For small companies, that can't afford to devote the time necessary to submit and manage these projects, there are specific schemes available and there are also firms of consultants who can be engaged to manage and monitor the operation of the project.

Dave warned of the potential for "breakdowns in communications" as the main reason why aspects of a project fail but, in general, the work was highly successful. The EC has carried out a cost: benefit analysis on the projects funded and has found that the C/B ratio is ~7:1. It also expects that it may be necessary to inject extra funds to see the development through to commercial exploitation.

Alison Crossley (AEA Technology, Harwell) discussed some medical and electrical applications of "joints" but pointed out that all the work done at AEA is carried out as joint projects because AEA technology has been set up as an independent contract research company. Alison has been involved with industrial sponsors, universities and various DTI, DOE and MOD groups. Currently she is associated with an ESPRIT funded project on scanning probe microscopy which is aimed at developing new electronic materials and micro- systems technology. AEA Technology also sets up R & D club activities and will manage European Commission sponsored work programmes on behalf of the participants.

Surface analysis and other techniques are used in collaborative studies of coatings and interfaces for tribological applications in orthopaedic implants such as hips and knees. There are 50k hips and 20k knee replacement operations per annum in Britain alone and the average lifetime of the joint is 10-15 years which is exactly the same as it was 30 years ago. The main technical reason for failure is corrosion and erosion (at ~0.1mm/year) as the metal spike rubs in an ultra high molecular weight polymer cup (to ensure a low friction coefficient). There are also biological problems with the adhesive used to bond

the spike to the bone. Modern methods that are being examined to improve the lifetime encompass (1) use of carbon fibre polymer composite systems for the spike, (2) ion implanted metals, TiN or diamond like carbon (DLC) for the wearing surface and (3) cementless implants where compounds of hydroxyapatite and phosphates are used to encourage the bone to grow into the implant.

Studies of electrical joints are carried out to improve stability, adhesion, ohmic resistance behaviour and compatibility with micro-patterning techniques. For high temperature contacts bonded to DLC, wide band gap semi-conductors are required. Collaborative studies using XRD and RBS are used to characterise the layer structure.

To provide ohmic contact, refractory metals are used which form carbides with the DLC. Titanium gives good carbide formation and the interfacial oxide can be made to dissolve in the metal such that stability is within 5% after 5000 hours at 800C. However, titanium will diffuse through a gold contact layer. This can lead to undesirable electrical characteristics and so a platinum barrier layer has to be employed. For molybdenum, AES studies show that oxide causes weakening of the joints. Collaborative effort and surface analysis all play a part in understanding the interfacial properties and reactions that occur.

Steve Harris (BAe, Bristol) described the vast array of "sticky topics" that the Sowerby Research Centre is set up to support within BAe's operations. Steve's group works on adhesion, diffusion bonding, welding, brazing, composites, sealants and electronic devices as part of internal partnerships within the BAe operating companies. They also sponsor fundamental work in universities. They have a Kratos XSAM800 and a VG ESCALAB MkII fitted with various fracture stages (bending and peeling) and a gas cell in which they can cure composites and paints under controlled conditions. The in-situ fracture stages are considered essential because they reduce confusion in interpretation resulting from post fracture reaction and contamination which occurs after ex-situ fracture.

As an example of the work on sealants, Steve described how XPS determined that a low peel strength failure from a polysulphone - aluminium bond was a cohesive failure in a weak boundary layer. SEM showed that this was due to the presence of an abrupt interface whereas high strength bonds are characterised by rough interfaces (ensured by suitable pre-etching) where a substantial amount of mechanical interlocking is also possible.

A contrasting failure mode was found for a multi-ply polymer system where a fluorocarbon de-bulking agent was incorporated at a very low level. Unfortunately, even at this low level, XPS showed that it had segregated to specific areas in the composite and, under mechanical stress, a crack propagated by following the line of least resistance through the segregated regions.

XPS and AES analysis of porous titanium welds was used to illustrate that the accepted wisdom is not always correct. The porosity was "known" to be due to hydrogen incorporation but surface analysis not only detected impurities but also found evidence that residual organic material was a more likely cause of the problem.

Steve's group have recently begun to use molecular modeling techniques to support the experimental studies. This is with a longer term view to validating the modeling approach and reaching the stage where it can be used to provide useful insights into the interactions in interfacial adhesion.

John Watts (University of Surrey) discussed collaborative studies that his group at Surrey had carried out on fundamental aspects of adhesion in conjunction with industrial sponsors. There is a difference in approach between engineers who like to couple the failure and degradation effects in their tests and the surface science approach which usually tries to separate them to aid interpretation of the failure mechanism. Commercial adhesives are multi-component formulations and the first chemical transformation stage occurs during curing. This leads to the initial interfacial chemistry which is further modified during environmental testing.

Using an example of an acrylic photo-cured micro-electronics encapsulant, John showed how a combination of XPS and SIMS was necessary to convince the formulators that an aliphatic diluent was segregating to the resin - ceramic interface and causing susceptibility to attack by water in humidity tests. John had used molecular modeling techniques to indicate that a monolayer of this type of material should adhere to the surface such that the molecules were tilted at 30 to the vertical and this would produce the 10nm thick surface layer that was found by XPS electron take-off angle studies. The water susceptibility was eliminated when this component was removed from the formulation but, unfortunately, it turned out to be a necessary viscosity improver which was essential in other applications.

John gave a second example of cooperation with industrial sponsors which involved resin curing for coatings applications. In this case, the formulators were using PF6 as an initiator. In SIMS studies the ratio of F- to PF6 fragments was shown to be an indicator of how far the curing had proceeded. Thus, the surface analysis results could be fed back to the formulators to indicate potential product modification which may lead to faster curing.

Finally, John described his philosophy of using XPS to obtain adsorption isotherms for the ingredients in a formulation and deriving the heats of adsorption. This data can indicate which ingredients are most likely to segregate to surfaces and reveal potential problems with the ultimate bond strength and susceptibility to degradation.

Gary Critchlow (ISST, Loughborough) described work on conversion coatings for aluminium, carried out in conjunction with industrial sponsors. Phosphates and chromates have been used successfully for many years but environmental considerations are forcing a search for equally effective alternatives.

Gary showed data which confirmed that the surface pre-treatment of aluminium had a dramatic impact on bond durability. Whilst a simple degrease gave a 70 hour time to failure, a combination of grit blasting, anodising and application of an adhesion promoter increased this to beyond 2000 hours when the test was stopped. The treatments are designed to produce surfaces that are micro-porous, clean, wettable and hydration resistant. AES, XPS and electron microscopies are required to characterise these properties of the substrate.

Using an example from the automotive industry where bonded aluminium joints are required to remain intact during a collision in order to absorb the energy of the impact, Gary showed that the surface magnesium oxide layer was first removed and a 40nm thick layer of phosphate was deposited as a nodular layer. There was an optimum thickness because thicker layers failed cohesively under impact using a variable mass pendulum test.

Results of studies using a zirconium based "green" alternative pre-treatment revealed that it is a ZrO_2 film that resists hydration and the ideal topography occurs at 50nm film

thickness. In tests at low load the treatment gives dramatic differences although at high loads these are less significant, probably due to creep in the layer.

Gordon Tatlock (IRC, Liverpool) discussed work on the adhesion of native oxides on Fe20Cr5Al alloys. In general, these materials grow a porous Al2O3 oxide scale at elevated temperature but the presence of sulphur, carbon and yttrium impurities can have a severe effect on the adherence of the scale. To investigate this problem, Gordon used FEM AES to analyse specially prepared high purity alloys free from these elements or with deliberate addition of them. In the presence of sulphur and carbon the scale morphology is convoluted and there are tunnels beneath the scale which appear to follow the grain boundaries of the alloy. This is clearly an indication of a weakly adherent scale. With addition of yttrium, at the 0.1wt% level, the scale is more uniform and apparently well bonded to the substrate.

Using thin samples which can be bent easily in the vacuum system using a wobble stick, Gordon was able to see that even the yttrium doped scale detached preferentially near to the grain boundaries. By contrast, the commercial grade alloys broke completely. AES analysis showed that the detachment seemed to be associated with sulphur or carbon in the large grain boundaries formed as a result of annealing. It was possible to map the apparent amounts of these impurities at the grain boundaries. However, this raised a question regarding quantification when applied to individual single crystal grains where channeling of the incident beam and diffraction of the emitted beam can give rise to preferential signal enhancement phenomena. It is known for example that a sub-monolayer of sulphur can dramatically alter the signal from a nickel substrate dependent upon the angles subtended in the spectrometer.

The work is continuing but Gordon warned of the difficulties encountered in very high resolution analysis of individual grains in an alloy.

Simon Church (IAC, Bristol) discussed his work on diffusion bonding of AlLi 8090 alloy using a novel development of a tensile fracture stage where it is used in reverse to apply a constant compressive load at elevated temperature, typically 66% of the melting point. The temperature was raised by placing the sample at one focus of twin elliptical mirrors and a 2kW halogen lamp at the other. The advantage of diffusion bonding is that it can be used to bond complex shapes with low deformation. Titanium bonds well by this method because it is capable of dissolving its own native surface oxide. However, for aluminium alloys, the native oxide has to be removed chemically or mechanically, by polishing. Polishing is not practical for a commercial operation but Simon has compared the behaviour of chemical etching and polishing in laboratory scale experiments.

Chemical etching produces porous surfaces compared to polishing. SIMS detects Li, Na, Al, K, O Cl with a significant amount of F on the chemically etched surface but much less on the polished alloy. XPS shows that the oxide remaining on the treated alloys is initially thin enough to detect the metallic aluminium in both cases.

Based on a set of 60 compressive shear test samples to expose the interfaces, Simon used AES to show that the oxide on a properly bonded alloy had a granular structure with a mixed Al, Mg and Li oxide. In contrast, a poorly bonded interface had grown a ceramic scale which was almost entirely Al2O3. Contamination elements Li, S, O, F, Cu, Mg and Al were detected beneath the scale. Simon's general conclusions were that, although chemical etching removes the native oxide it also introduces contamination. Joints formed

at low deformation allow air to enter along the interface and cause oxide growth. At high deformation pressures this is not such a problem. The art is to utilise the correct pressure in a production line environment.

Frank Jones (University of Sheffield) described the problem of obtaining convincing evidence that the chemistry of carbon fibre surfaces ranked equally in importance alongside mechanical keying in defining the strength of composite materials. His approach was to use plasma treatment methods to introduce functional groups to alter the surface chemistry without changing the physical surface roughness or to deliberately smooth the surface by using a non-functionalised coatings. The method involves plasma processing the fibres in a mixture of functional and non-functional monomers, e.g. acrylic acid and hexane or an ally-amine and octadiene. The ratio of the monomers defines the surface produced which was characterised using XPS. This showed that surface acid groups predominated at low power but hydroxyl groups at high power.

To correlate the surface chemistry with the bond strength, a single fibre fragmentation test was used which produces a mean length of fibre fragment that is related to the tensile load that the fibre-resin bond can support compared to the fibre itself. Frank found that part of the misunderstanding about the effect of surface treatments is due to the presence of inherent surface functionality on the fibres as manufactured. It then became possible to treat fibres so that the composite strength was reduced compared to the "as received" fibres. Amine and acid groups were then particularly good at improving the bond strength whereas hydroxyl groups were of limited value.

Applying finite element analysis methods to the composite has enabled Frank's group to propose a better method of characterising adhesion by use of the Composite Stress Transfer Function. The work has not only confirmed the importance of chemistry in fibre reinforced composites but has also highlighted the possibility of using plasma treatment methods to create graded bonds at the fibre-resin interface in the composite.

Simon Morton (University of Surrey) gave an update on the status of the UK ESCA User Group web site which can be found at:-

http://www.surrey.ac.uk/MSE/ESCA/ESCA/home.html

(the capital letters must be entered as shown).

This site is now the world's largest and most comprehensive web site dedicated to surface analysis. After only a very short time Simon and Chris Walker (University of Ulster) have produced an extremely professional, informative and technically useful facility which all members are urged to inspect in their own time. Meeting reports and future meeting information and registration forms will be available on the page to download directly.

Recent upgrades include elemental data from reference books by kind permission of the publishers. There is database of Auger parameters and other element specific information. The development of the Web site has acquired its own momentum and it is worth logging on fairly frequently to see what's new. The membership list (names and affiliations only) has been included so that individuals can make sure they are on the list or notify Simon if they or a colleague are no longer in the field and do not wish to receive our mailshots.

Simon ended his presentation with a request for members to inform him of information

that they would like to see on the site. All will be done to include items that are generally useful and do not infringe copyright.

The UK Surface Analysis Forum AGM

Dave Keast, the retiring Treasurer, reported that the Groups finances were in good order with the Group maintaining its contingency fund and breaking even over the year in operating costs. This would enable the Group to keep costs of meetings as low as practically possible in order to encourage younger researchers and technical staff to attend.

Len Hazell, the retiring Secretary, reported that the Group had run two very successful and well attended meetings at the Universities of Cranfield and Aston during the year. The mailing list had remained at ~280 with a roughly even split between members from industry, universities and government/service companies. The web site has attracted several requests from abroad to join the Group so it may be that the group has worldwide appeal rather than nominally being UK based.

Len reported that the Groups involvement with BSI and ISO standards evaluation was now yielding the expected benefits with many procedures and standardisation protocols reaching the final stages of acceptance. This will benefit all members in terms of improved instrumentation, recommendations for better laboratory procedures and data transfer and manipulation.

Elections.

After a brief presentation to Len and Dave for their work on behalf of the Group, several new members of the committee were elected. **Steve Harris (BAe, Bristol)** was elected Secretary, **Kathy England (University of Manchester)** was elected Treasurer, **Keith Hallam** and **Simon Morton** were elected to the committee for 1 year initially (to reinstate the biannual election cycle). Keith will have special responsibility for new members and Newsletter editor. Simon will now have an official role as web officer (webmaster).

EDITORIAL

Following the recent Committee reshuffle, I have taken over the proprietorship of the UK ESCA UG Newsletter from Steve Harris. As all new editors would say, if you have any comments, criticisms, suggestions, articles, adverts., etc. then do please get in touch with me (contact details at bottom of page), assuming the comments, etc. have something to do with the Newsletter, that is.

I have also taken over as custodian of the Archive. Please submit copies of your published work so that we can continue to maintain a library of relevant literature which can be made available to members, without the need to spend your money or hand over your precious inter-library loan tokens (Do other universities have restrictions on inter-library loan requests?).

Keith

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UK ESCA UG SCIENCE PRIZE NOMINATIONS

All members are invited to nominate papers from the calendar year 1995 for consideration for the UK ESCA UG Science Prize Award. It has been decided to merge the previously alternating categories of Science and Industry, and so work on either the fundamentals *or* application of ESCA may be put forward. The papers will be discussed by The Committee in January 1997 and the award presented during the July 1997 meeting. Please submit nominations to any member of The Committee (see web site for full list of Committee members) before the end of the year. Why not nominate your favourite papers at the same time as submitting your completed Services Questionnaire (see later)?

JANUARY 1997 MEETING

The next UK ESCA UG meeting will be held on Wednesday 15th. January 1997 in the University of Manchester Department of Earth Science. The subject of this meeting is The Surface and its Environment.

5TH. ISO/TC201 MEETING REPORT (Reporter - Bob Wild)

The 5th full meeting of the ISO/TC201 Committee, together with subcommittee meetings of SC1, SC2, SC3, SC4, SC5, SC6, SC7 and WG1 and WG2, took place in the Stakis Avisford Park Hotel, in Arundel, from Thursday July 11th. to Saturday July 13th. 1996. This is a brief report of the proceedings of those meetings.

The meeting was opened by Dr. Cedric Powell. Approximately 50 delegates attended the meeting, with Japan sending the largest contingent (22), followed by the USA and UK, each with 9, and 6 from Germany. Austria, China, Korea, Hungary and Sweden were also represented as were VAMAS and IUVSTA. The nine members of the UK delegation were Mike Wells, Albert Carley, Bob Bulpett, Alan Carrick, Peter Coxon, Steve Harris, John Watts, Alan Wirth and Bob Wild. VAMAS was represented by Martin Seah and IUVSTA by Dave Sykes.

SC1 - Terminology (Chairman M. Seah)

Martin Seah reported that WG1 had been terminated and WG2 formed to produce definitions of terms. A document has been produced by Martin Seah which is the first draft of the definition of terms. It has been prepared in four sections:

Techniques

Practical Items

Measurement Parameters

Scientific Components

Terms are listed with sequential numbering, e.g. 25 Resolution; 25.1 Resolution, energy etc., and where a term is used that is defined elsewhere it is typed in italics. Responses to this are requested by December 1996.

SC2 - General Procedures (Chairman W. Stickle).

Bill Stickle had taken over the chair of this committee from Charles Anderson, who had resigned.

SC2/WG1 - Specimen Handling (Convenor W. Stickle).

Two draft guides have been prepared with similar titles, Specimen Preparation, Mounting, and Analysis for AES, XPS and SIMS. The larger document is intended for the provider of a surface analysis while the shorter document is intended for the purchaser of the service.

SC2/WG2 - Reference Materials (Convenor W. Gries).

Werner Gries reported that a paper is about to be published that will form the basis of a proposed standard. His activity may be split into two standards, one for primary and secondary and one for working standards. Steve Harris reported on the need for future standards and requested that the heads of delegations be actioned to respond.

SC2/WG3 - Reporting Data (Act. Convenor S. Harris)

Steve Harris handed out draft documents on the reporting of results in: (i) XPS; (ii) AES; and (iii) SIMS/SNMS. There followed a brief discussion of these documents.

SC3 -Data Treatment and Management (Chairman D. Sykes)

Albert Carley reported on the years progress. In particular the progress in getting the NWI from WG1 (Data Transfer Format) from the Committee Draft to the enquiry stage.

SC3/WG1 - Data Transfer and Storage (Convenor M. Seah)

Martin Seah outlined the comments made by the US to the original data transfer format and although they had been accommodated where possible there was clearly a fundamental difference in views. The US delegation, led by K. Bomben, again argued

against this method of data transfer format becoming a standard and several short recesses were requested by the US delegation to consider their position. During these it was suggested that the US or Germany bring forward their own preferred data transfer format but that this format be allowed to proceed until superseded by the new format. This was accepted and the US delegation withdrew their objections.

SC4 - Depth Profiling (Chairman S. Hofmann)

SC4/WG1 - Definitions and Procedures (Convenor S. Hofmann)

Dr. Hofmann reported on the progress during the year on the SCA, Depth Profiling, Measurement of Sputter Depth. Experts had agreed to provide procedures for specific methods, including using a stylus, optical interference, angle lapping and ball cratering, cross section TEM and/or SEM, etc.

SC6 - SIMS (Chairman K. Tsunoyama)

SC6/WG1 (Convenor Y. Homma)

Dr. Homma introduced SIMS, Determination of Boron in Silicon Using Uniformly Doped Materials. Following discussion, it was agreed it should proceed to the Committee Draft (CD) stage.

SC6/WG2 (Convenor D. Simons)

Dr. Simons presented SIMS, Determining Relative Sensitivity Factors from Ion Implanted Materials. This is essentially the ASTM E1505-92 document which has been modified to form the proposed NWI.

SC5 - AES (Chairman D. Baer)

SC7 - XPS (Chairman J. Watts)

These two committees have much in common with two joint working groups. They therefore each dispensed with the bureaucracy before adjourning to consider the WG business.

SC5/WG1 - Quantification (Convenor C. Anderson)

Albert Carley presented the document dealing with the measurement of peak intensity in AES and XPS in which area methods and peak height methods are discussed. There was a view put forward that AES and XPS should be separate documents.

Dr. Sekine presented AES and XPS, Guide to the Use of Experimental Relative Sensitivity Factors for the Quantitative Analysis of Homogeneous Materials.

SC5/Study Group

Don Baer presented the results of a survey carried out during the year to rank tasks in their order of "Need" and "Status". The eight most important tasks were:

1) XPS BE Calibration

2) AES & XPS Sensitivity Factors

3) XPS Peak Areas

4) AES KE Calibration

5) AES P to P Heights

6) Background AES and XPS

7) AES Peak Areas

8) Area of Analysis in XPS

With the exception of 6 and 7, all of these are currently the subject of work to produce standards.

SC7/WG1 - Instrument Specification (Convenor J. Watts)

Dr. John Watts, Convenor, presented the draft new work items for discussion. The USA and Hungary both had comments on detail and would be submitting them to the secretariat.

SC7/ WG2 on Energy Calibration in AES and XPS (Convenor M. Seah)

Dr. Seah, described the new work item, Procedure for Calibration of Energy Scales of X-Ray Photoelectron Spectrometers. Detailed comments had been received from the USA. It is the intention to produce another working draft following receipt of all comments from experts before proceeding to the Committee Draft (CD) stage by 31/12/97

provides an ideal introduction to surface analytical techniques for industrialists meeting this area for the first time as well as a useful update for current service users.

Many of last year's attendees who were meeting surface analysis techniques for the first time were surprised at the information that these techniques could provide which was of ***direct*** benefit to their processes. They also found it valuable to learn of the technique limitations and alternative options for resolving complex materials issues.

You might wish to recommend this seminar to some of your colleagues.
The seminar programme is as follows:

2.30 p.m. Welcome and introduction

2.40 p.m. Practical Surface Analysis: Measurement and control of surface properties, introduction to the main techniques

3.15 p.m. Application Areas: Case studies from a range of industries

3.50 p.m. Afternoon Tea and Refreshments

4.15 p.m. Open Discussion: Sample selection, preparation and handling are discussed

4.45 p.m. onwards Consultancy Session (optional): Individual enquiries, including quotations and feasability of analysis, can be discussed with CSMA, in confidence.

Each ***regional seminar*** will be held in an easily accessible location with free car parking. We anticipate another positive response to this "training and awareness" exercise, and therefore recommend early registration. **We are offering reduced rates for group bookings.** £75+VAT per delegate (for one company representative), £60+VAT per delegate (for two company representatives), £50+VAT per delegate (for three or more company representatives).

Seminars are being held in:

West Country: Holiday Inn, Crown Plaza, Bristol, Tuesday 8th. October 1996

London, North/North West: Dean Park Hotel, Watford, Herfordshire. Wednesday 9th. October 1996

London, South/South East: Epping Forest Moat House, Essex, Thursday 10th. October 1996

Ireland, Medical devices/packaging: Ardilaun House Hotel, Taylor's Hill, Galway, Wednesday 16th. October 1996

Ireland, Electronics: Electronix '96 Exhibition, RDS, Dublin, Thursday 17th. October 1996

Please reply to Aruna Sibal, telephone 0161-237-5811, fax 0161-237-1008.

SURFACE SCIENCES SERVICES QUESTIONNAIRE 1996

If you wish to be included in the 1996 survey, please fill in the form below. Please note that the results will be used to form a number of tables. Therefore, the information you

send to me must be very clear. The forms must be returned to me at the address on the front cover by 30th. November 1996. Information will also be entered onto the User Group web site. If you do not want your details to be included on the WWW please make this clear.

Service or group name:

Primary contact person:

Address:

Telephone:

Facsimile:

E-mail:

URL:

Instruments and techniques available:

Specialised facilities (fracture stages, gas reaction cells, etc.):

Particular group expertise:

Additional information (e.g. non-surface analytical facilities):

Last updated 24 February, 2001

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