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onrl ltr, 8 jun 1971

TECHNICAL REPORT ONRL-16-67

OFFICE OF NAVAL RESEARCH

BRANCH OFFICE LONDON ENGLAND

Sheffield- Metallurgy's Capital

Jerome B. Cohen

15 March 1967

UNITED STATES OF AMERICA

TABLE OF CONTENTS

SHEFFIELD - METALLURGY'S CAPITAL

I. INTRODUCTION

The city of Sheffield is unique in many respects. It is at the foot of the Pennines just bordering a fine example of Midland moors, and close to some very excellent country eating. (Try ye olde Nag's Head in these moors if you get the chance.) Yet, although it is part of the "black country," as this industrial heart of the Midlands is often not very affectionately referred to, modern buildings and shops abound - quite unlike its grim neighbor, Manchester. Native Chicagoans will be pleased to note that they are not the only ones worrying about the poor reviews of plays in their newspapers and whether this will drive away the "big" shows. I read of a similar situation in the newspapers of Sheffield. This city is not, however, as some university literature describes it, one of the most exciting in Europe!

The steel industry of Great Britain was nursed into being here, and because of its history, the University's Metallurgy Group has an unusual status; it is a faculty on equal footing with the faculties of art, pure science, law, medicine, engineering, economics, and architecture. Materials research is greatly emphasized in this faculty, with Departments of metallurgy, ceramics with refractories technology, glass technology and a new postgraduate group - theory of materials. In addition, there are many fine industrial laboratories in the area - BISRA, United Steel, English Steel, and Brown-Firth.

This report covers materials education and research at the University and work at BISRA (The British Iron and Steel Research Association).

II. MATERIALS EFFORT AT SHEFFIELD UNIVERSITY

A. The University, Its History, Physical Plant and Students

The reason metallurgy occupies a unique position at Sheffield becomes quite clear when the history of the University is examined. Although a medical school was started in the early nineteenth century in Sheffield, it wasn't until the great success of a Cambridge University extension program in the 1870's that a college was founded. A steel magnate, Firth, built and endowed a school for arts and sciences, and as its President, Sorby was chosen. In 1882, however, the need for technical training was clearly shown when 100 students showed up for a set of lectures on metallurgy, whereupon a separate school under W.H. Greenwood was established. The three schools combined in 1897, and became a university in 1905. In 1917 metallurgy emerged as a separate faculty.

The buildings are situated along a line one and a half miles long from the center of the city to the western suburbs, if one includes the residence halls; however, the main buildings are in two groups, engineering and metallurgy being closer to the center of the city than the arts and sciences complex. Many of the buildings are quite modern in the now well-established "glassy-square" tradition. In the tall arts building, in addition to normal elevators, there is a continuous belt of cars one can hop on or off for short journeys, if one is wide awake!

The layout includes considerable room for expansion in the 1980's (Stage II as it is called), not only close to each faculty but also in the area between the two campuses, which are separated by about half a mile.

There are 830 staff members. At present the student body numbers about 4200 (seven times the pre-war number) and expansion to 10,000 is planned in Stage II. The graduate student body, about 600, is growing at about one and a half times the rate of growth of the undergraduate population. About a quarter of the students live in university residences, another 10% at home and the remainder in approved lodgings.

Because it is a relatively young university, and in the area of England famous for its non-conformity, it is quite forward looking in its student relationships. A student-health center was set up as early as 1937. With its dormitories, career assistance, and officer training corps, it is in fact very similar to an American university. Present research totals about one million dollars.

B. Metallurgy Department

(1) The Building

The Metallurgy faculty is larger only than the Law faculty, having about 6% of the total student body. Of the four departments of the metallurgy faculty the Metallurgy Department is by far the largest. There are about 85 graduate students (55 PhD candidates) and 150 undergraduates. The goal is 390 total. In addition, some 300 students are involved in night courses. Last year there were 84 freshmen in this field but since only about 60 or so can be accommodated until Stage II, requirements were tightened up a bit, resulting this year in a drop to 35 entering students. The teaching staff is about 20 (excluding half-a-dozen research fellows).

The Metallurgy Department's new building, with 12 floors, is lavishly equipped by any standards. The University

Grants Committee provided not only the building but $1.5 million of equipment!

Heavy processing equipment (forges, melting, etc.) are in the basement, a two-story high floor. The three top floors are adapted for individual research, rooms for graduate students, and a "hot" lab. Special laboratories such as furnace and vacuum construction, photography, metallography (with four closed-circuit television units), and machine shop are distributed on the remaining floors. Facilities for computer tape preparation are also available. Along with these features are, of course, offices, lecture and seminar rooms, etc. Most of the teaching laboratories are on two neighboring floors. The instructor's room is between two of the labs so he can watch both.

Included in the vast list of equipment is a microprobe, several electron microscopes including one small JEM for teaching, two table-model Philips X-ray film units for research, two older ones for teaching, a microfocus unit, two diffractometers (Siemens and Philips), about a dozen Philips powder cameras, a Joyce microdensitometer, spectrophotometers, semi-automatic X-ray fluorescence analyzer, direct reading spectrograph, and a mass spectrograph on order! Despite all this, someone was complaining that there wasn't a scanning electron microscope! Perhaps he will have one in Stage II about ten years from now, when the other departments in this faculty will have a chance to move from their much older quarters.

The new building has two drawbacks. First just as at Birmingham, it is far from attractive outside (although quite pleasant inside). Second, because it is vertical in organization, one is constantly running up and down stairs looking for people. A very expensive board was set up in the lobby on which the staff can move a lever to indicate they are in or out - very useful if one comes in late enough every morning!

(2) The Teaching Program

Probably largely due to the presence of the other departments in this faculty the undergraduate program in this Department is classical metallurgy, including a good deal of process and extractive metallurgy. There are several interesting features of the three-year program worth mentioning in more detail. Mathematical training stops after the first year or the second, if a student is not in the Honours stream. There are courses in failure analysis, statistics, electronics and one involving talks by industrial people (which has an exam). Some topics such as crystallography are spread out over the entire three years in small doses. A research project occupies a large part of six months of the final year.

The total number of lectures per year is about 260 - 270, plus tutorials, not vastly different than the number in an American program, if one excludes the humanities from the U.S. program (not given as you all know in the British programs). Although the students are better prepared at first, by the end of their three years and our four there is little difference in their technical training, at least from what I can see from detailed course outlines.

Surprisingly, there is very little given on electron theory. There is a course in dental materials.

There is an MSc program of one year of course work, and it is becoming a requirement for PhD candidates. The lack of this type course plus the rigid lines of authority in European universities, are the real weak points in their PhD programs; a doctorate from the US in my opinion involves much broader and deeper training.

(3) The Staff and Research Programs

"Q," as Professor A.G. Quarrell is affectionately called by his staff, heads up the Department, and has certainly done a marvellous job in "beating the bushes" to fund this outstanding building. (He has recently pointed out in a letter to the Times that in the last six years, 78% of the 101 advanced-degree English students who studied at Sheffield have stayed in England (there were 41 from the Commonwealth) - hardly a "brain drain!")) Prof. G.W. Greenwood is the second professor, from the Central Electricity Generating Board, Berkeley. (Prof. R.W.K. Honeycombe is of course now at Cambridge, and Dr. W.J.M. Tegart is now at Cranfield.) In addition, there are five senior lecturers, 12 lecturers and four research fellows. Some 55 publications came from this group in the last three years.

Prof. Greenwood is just getting his research group started. One of the areas in which he plans to concentrate is precision density measurements. By use of a dummy specimen, he believes problems such as temperature control are minimized and that a precision of 1 part in 10^6 will be possible. Three main areas are involved in his plan: (1) effects of deformation and perhaps faulting, (2) effects of quenching in very dilute alloys, and (3) creep. In this last area he has three main projects in mind. First, he is interested in examining changes in density as a function of the rate of grain-boundary sliding to detect void nucleation. This study will be coupled with transmission electron microscopy.

Secondly, hydrostatic pressure will reduce the driving force for vacancy motion to voids in grain boundaries; thus, by starting voids in creep and then superimposing hydrostatic pressure to stop their growth, the interaction of these voids with dislocations can be studied. Also, as these voids have never been exposed to an atmosphere, he intends to study their coalescence to test sintering laws in these ideal circumstances.

Greenwood's long-standing interest in Herring-Nabarro creep continues, and he would especially like to examine this at low temperature. To do so he plans to load a specimen in the shape of a spring, to obtain the necessary very low strain rates. Particularly, he intends to try to discover why grain boundary precipitation lowers the creep rate.

Dr. C.M. Sellars (lecturer) collaborated with Dr. W.J.M. Tegart on studies of hot working, but will now be heading this group here on his own, because of Tegart's departure. It was refreshing for a change to find that electron microscopy was <u>not</u> applicable to his problems. The dislocation arrays developed are too non-uniform. The arrangements are "loose" and on thinning too much is lost or rearranged. Satisfactory correlations with etch pits could <u>not</u> be obtained. The microscope is then used mainly qualitatively to see if sub-boundaries are well developed.

After Fe-Ni alloys are deformed in hot torsion, they are recrystallized, but it wasn't certain initially whether this occurred <u>during</u> the deformation or on subsequent cooling. The former is the case; with the strain constant over four orders of strain rate and regardless of the temperature of the test, the flow stress (<u>at</u> temperature) was proportional to the recrystallized grain size. Similar studies on Fe, Al are under way. Low purity iron (worked in the α phase region) and Cu also recrystallize during hot torsion, but Al and high purity iron form subgrains, apparently because recovery is rapid. If there are "rests" between stages of the deformation in order to simulate hot-working practice, recrystallization may occur in those materials that only recover during uninterrupted hot working. The group is attempting to dope the pure material (iron) to find out what element causes this transition; O_2 is the first element being tried.

Sellar's group is also involved in studies of creep in Stage II, particularly grain-boundary sliding, effects of subgrain size, and density of mobile dislocations (within subgrains). Some of their results are illustrated in Fig. 1 (σ is the creep stress, ρ is the mobile dislocation density).

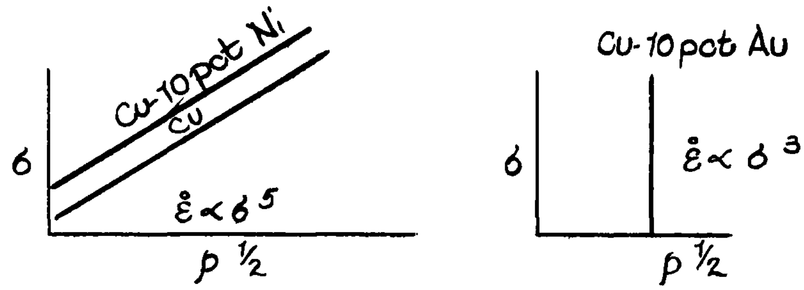

Fig. 1.

In Cu and the Cu-Ni alloy, Sellars thinks the dislocations move quickly to tangles or subgrain walls, and that recovery within these arrangements is rate controlling. In the Cu-Au alloy he believes the rate-controlling step is the Peierl's stress, i.e., motion from the source is difficult. Of course, the results for Cu-Au imply very large changes in the dislocation content of subgrain walls with stress, but these are too dense to examine by electron microscopy.

Two other areas of work are included in his interests, one of his students is setting up equipment to measure Young's modulus <u>at</u> temperature, as this quantity so often appears as being raised to a power in theories of deformation. Secondly, he is studying the effect of hot torsion, or tension, or fatigue, on carbide coarsening in ferritic steels. Six orders of the strain rate are being covered, and Fe_3C and $Cr_{23}C_6$ are the carbides primarily being examined. Extraction replication is the primary tool.

In results to date on Fe_3C in 0.2 C - Cr containing steels, plots of the volume vs time give two slopes. Only the one at long time yields a reasonable interfacial energy. The slope at shorter time gives too large a value, but it is thought that this is because the true diffusivity may be much bigger than that employed in the calculations, perhaps because dislocations (where the carbides nucleate) in the martensite are acting as short circuits for diffusion, until the particles are quite large.

The reason previous investigators have often found little correlation of initial structure with creep rate in steels with chromium carbides is because when the temperature of the test is reduced rapidly, the precipitating carbide does not come out on existing particles, but on a very fine scale instead.

Dr. J.H. Woodhead (lecturer) is studying low alloy ferritic steels, particularly Nb and Nb-Mn-Si. This area, of considerable interest throughout the UK, has already been explained in detail in my report on NPL (ONRL-13-67). Woodhead's results essentially fall into this discussion and so I will not describe this area further. He does feel, however, that the rows of NbC often seen in these steels may come from decomposition at the α - γ phase boundary. They are somehow left behind by the moving interface.

He is actively studying precipitation sequences in Cr, Mo and W steels. Also by adding Nb and V he has found it possible to extend the useful range of low carbon alloys by impeding grain growth. NbC can be produced in an aging treatment, and although it coarsens at relatively low temperatures, VC is then forming.

Woodhead has a large interest in quantitative metallography. At the moment, he is examining whether or not the ratio of the standard deviation to the average grain size is a fixed ratio, independent of grain size in recyrstallized specimens. This seems to be true in cubic materials, but from data taken by Andrade, the ratio is much smaller for hexagonal materials annealed for very long times. He is now doing similar long anneals with Al to see if the ratio in cubic materials falls with time; preliminary results suggest that it does. The entire grain size distribution is being obtained after each anneal.

Woodhead is also studying pearlite nucleation and growth, using a modified Scheil analysis to convert the measurements on a plane to volume data. His procedure is sketched in Fig. 2. If N is the nucleation rate, and d the colony diameter, he finds the following power laws satisfactory:

$$N = Kt^{n}$$

$$d = ct^{m}$$

$$\frac{\text{Number}}{\text{Unit area}} = K' t^{m+n}; \text{ volume fraction} = K'' t^{3m+n}$$

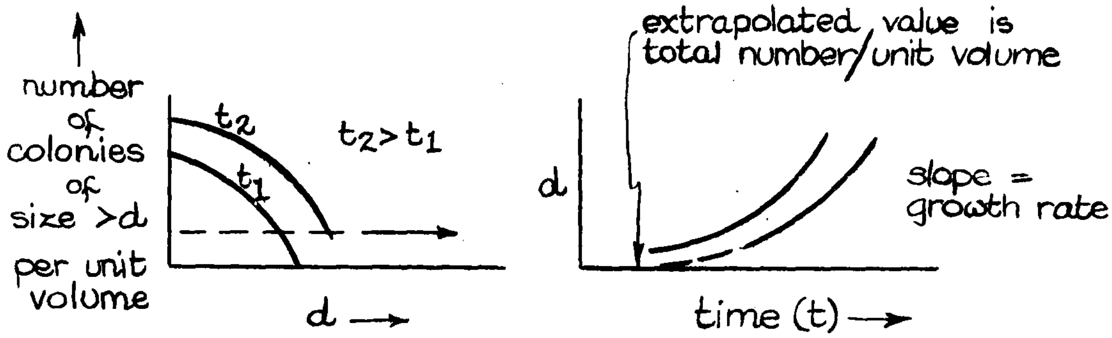

Fig. 2.

Dr. J. Whiteman (lecturer) and Dr. S. Murphy, a research fellow, are pursuing Murphy's PhD work on carbide precipitation in 0.2 C steels, with particular attention to the chi carbide reported by Russian investigators, and ε carbide. They believe that neither of these are separate phases, but merely a defect form of Fe_3C, low in carbon. In Murphy's thesis, measurements of the Curie temperature of the carbide indicated a continuous change in C content as it formed. By examining the (100) cementite plane and (110) ferrite plane, they have worked out that a twinning shear on a (112) plane of ferrite and some expansion perpendicular to this plane (plus interstitial carbon of course) will yield cementite. Indeed, in electron diffraction studies they find streaking at the carbide diffraction spots perpendicular to (112) when these spots first appear. The necessary shear, they believe, occurs in the quench, and some thickening of microtwins occurs and then carbon orders in these regions, which gradually develops into cementite. As part of this ordering scheme, unit cells have been devised which do, in fact, account for the diffraction spots from ε carbide.

Whiteman is also studying the possibility of hardening the ferrite in low C steels with intermetallics. At the moment, he is trying to find out why Fe_2CoTi is a hardener but Fe_3Co is not, and why Fe-Si-V or Fe_3Al plus a third element do not cause hardening.

Dr. D.H. Warrington (lecturer) is studying decomposition and devitrification of glasses, denuded zones in Al alloys, effect of stacking fault energy in steels on precipitation, subgrain formation in austenitic steels, and deformation of cementite.

B.B. Argent (Senior Lecturer) is using an adiabatic calorimeter and an isothermal "drop" calorimeter (into organic liquids) to examine the enthalpies of formation of martensite.

A. Kay (lecturer) is involved in studies of extraction metallurgy, particularly electro-slag refining. (He is an expert on smoked salmon and the liquid products of Scotland!)

Drs. J.M. West and N. Birks (lecturers) are carrying out research on corrosion, stress corrosion, and oxidation.

Dr. C.W. Haworth (lecturer) has a program which involves the use of the microprobe in metallurgical studies. One such study concerns the cause of grain boundary hardening in iron base alloys. He is also planning to study surface diffusion of Cd, Zn or Cu, and Ag. At the moment, he is checking the results from Harvard on interstitial diffusion of noble metals in Sn.

In the Cu-Co system, Haworth has found an unusual effect; close to a coarse particle of cobalt, the cobalt concentration is much higher than would be predicted from the phase diagram. The data taken with the microprobe needed the usual corrections, and this result involves extrapolating the concentration some distance from the particles, using the error function,so more work is needed. However, there is not any question about the influence of a compositional dependent diffusivity; the composition changes involved are too small for this to be important.

The other three departments in this faculty share a common first year with the Metallurgy Department. Then, there are separate curricula, except for the theory of materials, which is not given in the undergraduate program, but is primarily a graduate department.

C. <u>Theory of Materials</u>

Prof. B.A. Bilby has formed his own group, housed a few blocks from the Metallurgy Department, in Glass Technology's building. My own opinion is that this is unfortunate, as both groups will suffer from the reduced contact. At any rate, a new MSc program will commence next fall and consist of an unusual combination. About half of the lectures will be given by the Applied Mathematics Department in computer programming, and numerical and analytical solutions to partial differential equations, and the other half (60 lectures) given by the metallurgy staff will be on dislocations, diffusion phase changes, plastic flow, strength.

There are four staff members in addition to Bilby - J. Eshelby (Reader), C. Atkinson and N. Fox (Senior Research Fellows) and B. Gale on leave from NPL. Both Eshelby and Gale have just arrived.

Bilby is performing computer calculations on dislocations feeding a crack from a slip plane. Eshelby has just finished some calculations on a crack expanding in two directions. There has been some conflict in the literature, but he finds that the crack does reach the material's Rayleigh velocity.

It is hoped to add a polymer man to this group.

D. Ceramics with Refractories Technology

Prof. J. White, whose work on ceramic phase diagrams is well known, leads this developing department. They are housed comfortably in portions of the old metallurgy building. The department was started by White in 1956. The staff has grown rapidly in the last few years, and I list their names with arrival date and interests:

Name	Arrived	Interests
D.W. Budworth	1963	Fabrication
Dr. W.F. Ford	1964	Mechanical properties of sintered materials; microprobe
Mr. N.H. Brett	1964	Topotactic reactions
Dr. G.C. Bye	1965	Sols, gels
Dr. J.H. Sharp	1966	Solid-state reactions

There is still one vacancy on the teaching staff. There are five undergraduates in the final year, one in the second and three registered in the first year. Of the 12 graduate students, three are studying for an MSc, the rest are PhD's. This Department has had as many as 17 graduate students.

White continues to pursue his studies of phase distributions in refractory brick, with particular attention to effects of interfacial energies. With two solid phases (A,B) and a liquid (CoO- MgO- silicate) he finds more A,B contacts than A,A or B,B.

Budworth has learned to make fully dense Al_2O_3. Additions of MgO, NiO, and CoO all work, and all are volatile oxides. Variation of the firing atmosphere indicates that conditions must be right for spinel formation with alumina. Apparently this occurs on the powder surfaces through the vapor; the spinel then slows up grain boundary migration sufficiently so that the boundaries absorb pores. The spinel is not molten. A simple test shown below supports this hypothesis, but there is still no direct evidence for spinel at the grain boundaries other than exaggerated grain growth after a long time. SnO_2 is also a successful additive, even

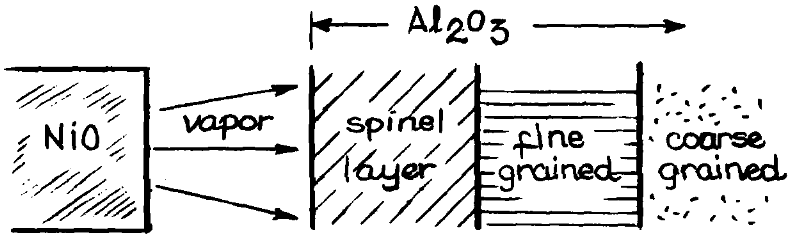

Fig. 3.

though it does not have any appreciable solubility or form compounds. In this case, unlike the others, grains are elongated. Budworth has also made fully dense MgO using NaF or LiF additions. With the NaF, he may be able to find its whereabouts with a microprobe.

Brett's work involves structural relationships between product and original materials, for example, $Ca(OH)_2$ decomposing to CaO at 400 - 500°C. The product phase from a single crystal of the hydroxide is at first also single crystal and oriented, and then recrystallizes into a polycrystalline aggregate.

He is also preparing spinel precipitated in MgO from mixtures of $Fe(OH)_3$ and $Mg(OH)_3$. Finally, he is looking at the $CuO-SiO_2-ZrO_2$ ternary, with the hope of finding a high melting phase to use as a new refractory.

Bye is examining the processing of ferrites from ferric oxide and $BaCO_3$ to determine how the condition of the powders affects firing.

The Department has a Philips diffractometer, and a Nonlus-Guinier camera, a Philips-100 electron microscope, a microprobe, glove box, Instron, and a nice diamond work shop.

E. The Physics Department

Just a brief mention will be made of the activities in this Department, relative to research on materials.

NiO and CoO single crystals have been successfully grown by a new method, and studies of electrical properties are being made (see I.G. Austin, A. Springthorpe, B.A. Smith and C.E. Turner, Proc. Phys. Soc. 90, 157 (1967)).

Prof. G.E. Bacon, here from Harwell three years ago, is pursuing his neutron diffraction studies of Pt_3Fe. As excess Fe is added the antiferromagnetic spin alignment changes. At stoichiometry, alternating ferromagnetic (110) sheets of Fe are coupled antiferromagnetically; but with excess Fe the ferromagnetic alignment is on (100) sheets, and superparamagnetic Fe clusters, coupled internally ferromagnetically, exist above the Curie temperature (see Proc. Phys. Soc. 88, 929 (1966)). Field ion microscopy is planned on these alloys, to try to detect details of the local arrangements. Work on the Au_2Mn_2 - Au_2MnAl series is just being finished. The first is antiferromagnetic, the second ferromagnetic, and mixed states occur in between, including a spin with a 90° "twist."

Bacon still goes to Harwell every two to three weeks; his students stay there during their experimental work.

III. B.I.S.R.A.

The activities of the British Iron and Steel Research Association are well presented in their annual report, available on request. I shall therefore cover only some of the highlights, and developments since their latest report.

A. Organization

Briefly, this is a research organization with several laboratories, of which the principal ones are in London and Sheffield. The annual budget is aboug \$4 million, three-quarters of which is paid for by its 400-member firms by means of a fee based on production tonnage. About one-quarter of the budget comes from a direct government grant. In addition to these sources, as much as 8% of the total can be added in the form of direct contracts with individual firms. This, however, is an over-all figure; it varies from one division to another and is as high as 30% in the Metallurgy Division. In this way, even though a concept may not be appreciated or supported by top management, it is still possible for an individual group to carry on with their ideas, if support can be found.

The organization is directed by a council whose members are from industry and the Ministry of Technology. The organizational make-up under this council is in the form of divisions covering the entire gamut of ferrous metallurgy, including a large operations research group concerned with the applications of computers to industry. There are also a few small departments such as Physics and Chemistry which develop their own work and also support the main divisions.

Mr. W.E. Duckworth coordinates metallurgical activities in all divisions for the council. The main metallurgy division, headed by a dynamic young Scot, Dr. R.L. Craik, is in Sheffield. As an example of the composition of a division, this one is broken into groups called physical metallurgy, engineering, properties, electro-slag refining, special steels, analytical chemistry, secondary processing (i.e., degassing, etc.), and finally, there is a development group selling know-how in setting up plant practice, exchanging information, etc. In this Division there are 80 - 85 people, 20 - 25 of whom are "professionals."

Most of the activities of BISRA are concerned with advising on and solving operating problems, and originating new technology including setting up pilot-plant operations. Fundamental studies are handled primarily by supporting work in universities under contract.

B. Corrosion Studies (London)

This group, headed by J.F. Stanners, is part of the Chemistry Department. Molybdenum-containing stainless steels would be required in UK for architectural use because of the special weather conditions. Because these steels are somewhat more costly than those used in the US, less is employed. Investigations are under way to examine the behavior of such steels in use and also what can be done to improve corrosion resistance. Methods are being studied to improve PVC coatings, particularly in damaged areas such as welds.

This group is working on the usual simulations of actual "weathering" in the laboratory and at field stations, with special attention being given to low alloy steels (up to 1.5% total alloy content). Studies will soon start on steels with up to 5% of alloying elements. Some work is under way to examine whether pitting can be simulated in the laboratory. Movie films are being taken of carbon and silica particles on a polished steel surface, exposed to various atmospheres, to see whether these or inclusions in the base metal are the cause of the breakdown of the passive film. SO_2-containing atmospheres are used, since it is known that $FeSO_4$ is one of the most important agents in causing pitting.

Attempts are being made to develop rapid tests for paints in view of the fact that new ones come on the market almost daily. The resilience of a paint layer is being tested for a few months by periodically measuring the recovery of an indentation and also the stress necessary to push a wedge into the edge of the layer. It is hoped to correlate these with long-term tests of behavior under field conditions.

A "corrosion advice bureau" is available for trouble-shooting and some literature is available on request concerning the proper selection of steels and design principles to minimize corrosion.

C. Physics Department (London)

E.W. Voice is the head of this Department. A new process has been developed to clad ordinary steel with stainless. After a flash of Cu, hot rolling is used to create a diffusion bond. The cost is about half that using other methods. Co-deposition processes have been considerably developed, and the section has successfully produced Cu deposits with SiC for wear resistant surfaces, or with graphite to act as a lubricant. Alloy layers of specific compositions can also be developed.

There is some activity on composites and the group has successfully used piano wire as a reinforcing fiber. By electroforming copper tubing while winding on such wire, a composite has been produced which can withstand substantially larger hoop stresses than can copper alone.

The "Elquench" process developed at BISRA appears to be getting some commercial use. By applying a variable potential between a piece and the container of the quench media the vapor blanket is affected. The quench rate can be adjusted over a wide range. Cheaper steels can be hardened without too much distortion. Another use is localized hardening.

(During my visit to the London labs, a number of television sets could be observed in various labs showing a mini car on their parking lot. Apparently, a number of cars had been stolen and, as the police were not too helpful, they decided to try to "nab the culprit" on their own by placing an unlocked vehicle in the lot. If any of the staff saw the theft in progress, they were to race down to the lot and presumably catch him. I wondered how they chose those who had the sets.........)

D. Iron-Making Division (London and Sheffield)

"Slagceram" is a glass ceramic developed at BISRA in the Iron-Making Division about four years ago. It is made of slag with its composition adjusted by additions of sand, with transition metal oxides as nucleating agents. Experiments are continuing on its properties and to learn to control the processing better. Pilot plants are in operation. Suitable techniques for measuring the glass and crystalline content (to correlate with strength) have not yet been found. Of particular interest is the fact that combinations of two of the nucleating oxides serve as better agents than do either of the pair individually; the reasons for this are being examined.

E. Steel-Making Division

Under Dr. J. Pearson, this Division has developed a brand-new refining process -- spray steelmaking. Liquid metal directly from a blast furnace is sprayed into a chamber where reactions with oxygen refine the steel. A continuous on-line process with a blast furnace is feasible, as 30 tons per hour can be handled. Several mills are installing units. However, there is still some question as to whether this process will work with other than very high-grade ores.

F. Metallurgy

In electro-slag refining an arc is struck between an electrode of the steel and a piece of the metal mixed with slag in a mold. The steel and slag melt, the electrode moves in to the slag and slowly dissolves, dripping through the slag and being refined. The melt solidifies in the water-cooled mold as it passes below the slag. This process is now being studied here for three European countries as well as for British companies, and operation is starting in several mills. Expected tonnage is confidential as yet. There are a number of advantages to the process: It can readily be adopted to continuous computer control. Sulfur, oxygen and phosphorous, and easily vaporized alloying elements are readily adjusted. Single-phase operation is possible. Inclusions are reduced to a fine distribution only. Ingot yield is improved by providing a sound ingot end to end, thus helping to pay for the process. Eight-inch diameter ingots or 7-in square sections have been made.

The slags must be conducting, so a base of spinels and/or CaF_2 is employed. Composition is adjusted to provide proper refinement and a uniform coat on the ingot, thereby improving surface finish. The slag is pre-melted and pulverized just before use, otherwise, moisture pick-up would lead to large hydrogen content. Much work is being done on the right slags for a variety of steels, and the group involved in this effort is essentially completely supported by contracts from interested concerns. Incidentally, the removal of oxides seems to involve reducing the inclusion in the slag and then reoxidization of the elements involved in solidification of the alloy. Thus, it may be possible to <u>introduce</u> finely dispersed phases by reactions with the slag.

The Division has learned how to grow large single crystals of Ni-base, Co-base, and Fe-base alloys. They have found this to be relatively easy <u>if</u> vacuum-melted alloy is used as a starting material. Many properties will be studied, but at the moment the emphasis is on magnetic properties (crystalline anisotropy, permeability and magnetostriction) in order to find more suitable compositions for Fe-base alloys.

There is a large effort on thermo-mechanical treatments. Work concerned with finding the right rolling temperatures, Nb content and cooling rates to obtain a low-grain size in the finishing passes on low carbon - low alloy steels is still going on. At the moment, finishing temperatures are too low and occasional damage to the rolls is feared.

Ausforming is being studied with particular emphasis on its effects on the S-N curve. This is shifted to the right so that although the fatigue life (and toughness) is not improved, higher stressing is possible.

Particularly notable is their work on "isoforming." Deformation during transformation at the pearlite nose of a low alloy steel produces a spheroidal carbide which also holds the ferrite grain size down. Strength is improved and toughness is markedly increased. The structure is stable well above the temperature of the process, and procedures for carrying out this process during the continuous cooling characteristic of usual rolling operations have been developed.

The mechanism for this change in microstructure is not clear. Is it vacancies produced by deformation? This seems unlikely as the temperatures involved are in the vicinity of 650° - 750°C. At any rate some thought is being given to trying a similar process on hypereutectoid alloys (with the hypoeutectoid steels, sections up to 3/8-in thick with uniform structure have been produced).

Studies of fracture toughness in stress corroding environment are being carried out, with particular attention to the fact that the critical stress intensity factor (K_{1c}) seems to fall and then level out with time. The minimum value bears no simple relation to the value in a non-corroding environment, and a higher value in such a test is no guarantee that a lower value will not be obtained in a corroding environment. Along with this work a comparison is being made of impact tests and the techniques of fracture mechanics in predicting toughness.

In Ni-base austenitic steels additions of Ta produce a precipitate of Ni_3Ta which is initially coherent, but is incoherent and orthorhombic at peak hardness. It is hoped to build on this base with additions of Ti, and Al to achieve additional hardening from γ'.

G. Concluding Remarks

It should be clear from this brief description that BISRA is an active organization whose efforts are "paying off." Unfortunately, the possibility of nationalization has been hanging over the British steel industry for three to four years, so implementation of new processes has been slowed a bit by a lack of interest in spending any money until the government plans are clear. These seem to be shaping up now into essentially a geographical regrouping to meet market demands and eliminate excessive competition. Thus, the impact of this all-industry group will increase in the next few years. It could be hoped too, that some of the more basic work required will be done "in house." While the present scheme of giving out contracts to universities, particularly to consultants, may keep the academic world more in touch with the needs of the British steel industry, it is my own feeling that: (a) in many areas BISRA is, and will be, uniquely equipped to do the job; (b) the in-house effort should prove stimulating; (c) there is considerable work on precipitation in low carbon steel and on electro-slag refining at Sheffield University, but it is not sponsored or connected in any way to BISRA in Sheffield. This clearly indicates that BISRA's support of basic work involves, in fact, only quite limited funds. The size of the steel industry in England is certainly large enough to warrant a larger effort, and it is clear that the support of outside work is too easy to avoid.

UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Office of Naval Research, Branch Office London, England	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b. GROUP

3. REPORT TITLE

Sheffield - Metallurgy's Capital

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

N.A.

5. AUTHOR(S) (Last name, first name, initial)

Cohen, Jerome B.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
15 March 1967	18	

8a. CONTRACT OR GRANT NO. N.A. b. PROJECT NO. c. N.A. d.	9a. ORIGINATOR'S REPORT NUMBER(S) ONRL-16-67 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) N.A.

10. AVAILABILITY/LIMITATION NOTICES This document is subject to special export controls & each transmittal to foreign governments or foreign nationals may be made only with prior approval of the Office of Naval Research Branch Office, Box 39, FPO, New York 09510.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
N.A.	N.A.

13. ABSTRACT

The Metallurgy Department's building and research in the metallurgy faculty at the University of Sheffield are described. Work at BISRA is also discussed.

14. KEY WORDS	LINK A		LINK B		LINK C	
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Metallurgy, BISRA, corrosion, composites, slagceram, electro-slag refining, single crystals of Ni, Fe, Co base alloys, thermo-mechanical treatments, ausforming, isoforming, Sheffield University, hot working, creep, voids neutron diffraction, fully-dense ceramics, topotactic studies.						

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