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Panel discussion

Moderator:	Prof. S K Joshi, Department of Physics, Roorkee University
Panelists:	Dr R Krishnan, Metallurgy Division, Bhabha Atomic Research Centre
	Dr V C Sahni, Nuclear Physics Division, Bhabha Atomic Research Centre
	Dr S Ray, Metallurgy Department, Roorkee University
	Prof. N Kumar, Department of Physics, Indian Institute of Science

Prof. Joshi: We have had a busy and very fruitful Discussion Meeting. This is the last session, and we are gathered to hear the reactions of the panelists, as well as their suggestions. There are no restrictions or guidelines, and the panelists are completely free to express what they feel. I shall alternate between metallurgists and physicists, and will start with Dr Krishnan.

Dr Krishnan: During the past three days I have informally talked to many of the participants, and I have come to the conclusion that this Meeting has been a unique experience. I suggest it should continue as an annual feature—if not on the same subject, at least on topics of an allied nature.

A general remark I would like to make is that many of the theoretical papers have shown that it is necessary to take the theoretical aspects more seriously and also utilize mathematical and physical concepts in explaining some of the behaviour of materials. On the other hand, I also felt that perhaps it is not necessary to explain some of the well-accepted observations the metallurgists have made. It would be more useful to complement the metallurgists in a suitable manner.

One topic not fully discussed at this Meeting is fracture. Why are we interested in obtaining a better understanding of the physical basis of mechanical behaviour? Essentially it is so that one can design better materials which will withstand service conditions. For instance, one might be interested in designing a material with good fatigue resistance or good creep resistance. We know that materials can fracture in widely different ways—ductile, brittle, cleavage etc. On the opening day, Prof. Ramaseshan has already pointed out how important it is to know the stress corrosion cracking behaviour of materials under service environments.

Take the nuclear field as an example. The iodine produced as a fission product can interact with the zircaloy clad and make the clad susceptible to stress corrosion cracking. The basic question here is: What does iodine do under stress to the grain boundary? Is there a decohesion caused by a lowering of the cohesive energy of the grain boundary which is locally under stress? Is it possible to predict which atomic species (like iodine) are efficient in lowering the cohesive energy? Theoretical studies of this problem coupled with suitable experiments will go a long way in establishing interplay between physical concepts and metallurgical interests.

Another example, again from the nuclear industry, relates to the irradiation creep behaviour of zircaloy coolant tubes. While the reactor itself has a life span of about 30 years, one is forced at present to change these tubes once in every 12 yrs or so because of irradiation creep. To develop a material that will be good for the entire life span of the reactor, we must perhaps introduce new ideas. One should examine how the texture (*i.e.* the preferred orientation) and grain shape influence irradiation growth of the material. Perhaps, as Prof. Ranganathan suggested, one could use the concept of fractals to characterize grain shape topology— and thus have a better measure for studying and characterizing irradiation growth.

These are some examples of practical problems where there can be a meaningful dialogue between physicists and metallurgists. They involve finding real-time solutions to real-life problems based on an understanding of the basic behaviour of materials.

Prof Joshi: Thank you, Dr Krishnan, for pointing out some problems where physicists and metallurgists could come together. We now turn to Dr Sahni.

Dr V C Sahni: I would like to go back to the remark which Dr Venkataraman made on the opening day. He was looking at a certain matrix element and trying to find out whether it would be zero or non-zero at the end of the Meeting. Now metallurgists are essentially practitioners. In fact, you would have noticed this from Dr Krishnan's remarks. On the other hand, physicists are a different kind of people. They tend to look behind a phenomenon, try to understand it from an atomistic basis and so on.

An analogy comes to my mind at this point. Consider the automobile engine. Obviously there are (automobile) engineers who design such objects. But there are also people trying to understand the basics of the combustion process *via* tools like Raman scattering. The hope is that such basic studies can lead to the improvement of the efficiency of the engine.

Physicists cannot from the word go come up with solutions to the practical problems of metallurgists. The important thing is they try to analyze the microscopic basis for a particular type of behaviour. In turn, the metallurgist can build on this instead of relying on a phenomenological understanding of the situation. Of course this is the way science progresses.

So, coming back to the point Dr Venkataraman made about whether there is an overlap matrix element or not, I think we really have to look at the interface between the two disciplines. As Prof. Ranganathan's talk clearly brought out, a topic like the large-angle grain boundary is something which physicists can examine from an atomistic point. If some light is shed, then perhaps it will enable the metallurgists to come up with better materials. In short, physicists can *via* tools of their own (like fluctuation spectroscopy) explore microscopic processes which in turn can form inputs to the metallurgical aspects. So my own view is that the matrix element might not be as large as one would hope for, but it is not zero either. I am in agreement with Dr Krishnan that exercises like this Meeting should continue. Hopefully, if we repeat it a couple of times, we may converge on something significant and improve the matrix element in the future.

Prof. Joshi: Thank you, Dr Sahni. I think the value of the matrix element depends on the "frame" of reference just as Deepak Dhar pointed out that the length of a coastline depends on the length scale used for measurement. Locally the matrix element is sometimes positive and sometimes negative. What we must all do is to go to a scale where it becomes *globally* positive! I now request Dr Ray to give his views.

Dr Ray: Before we try to explain the mechanical behaviour of a material, we must first define the mechanical *state* of the material. Important in this context is a proper description of the grain boundary concerning which Prof. Ranganathan described a beautiful model. However, from the questions that were raised after that talk, I can see that there are limitations to that model. One wonders what the correct description of the situation at the grain boundary should be. May be something will emerge in the future.

One topic on which we did not focus is vacancies, especially their role in defining the mechanical state of matter. Vacancies play an important role as we know from annealing experiments on cold-worked samples. They are also pertinent to certain aspects of plastic deformation.

Next comes the grain shape. We all know that the grain shape is probably important but we do not yet know how to describe it quantitatively. Probably, the fractal concept might help us.

Let us now consider the transition from the elastic to the plastic regime. We used to think of this in terms of dislocations becoming mobile and multiplying. Now they are being described in terms of fluctuations, bifurcations, chaos and what not! Incidentally, I would like to point out that for bcc metals, there is a temperature below which this transition does not take place; for fcc metals however, this does not hold. All facts taken together, the picture to my mind is a bit puzzling. Is the elastic to plastic changeover really a transition or the emergence of a stable fluctuation of a particular kind?

Prof. Joshi: Thank you, Dr Ray. I now invite Prof. Kumar who has all along been making illuminating remarks from the floor, to give us his views as a panelist.

Prof. Kumar: I believe it is a part of conventional wisdom (which goes back to the Greek philosopher Lucretius) which says that a thing is explained only if it is done in terms of underlying microscopic objects (which, one presumes, exist). This may be a mental bias but no one seriously questions such an approach now. Certainly it is a part of our training as physicists. The question therefore is: What is the appropriate level of microscopy at which we want to discuss the present problems? Certainly you don't start with quantum mechanics if you want to build a house! There must be an "efficient" relationship between the microscopic world and the phenomenon we wish to understand. Of course all phenomena are not easily reducible to microscopic pictures. That we shall bear in mind. Now I shall get down to something specific.

Physicists often work with paradigms. For instance, if we are talking about a solid, we immediately imagine a perfect crystalline lattice and invoke Bloch's theorem. Everything is fine. Any departure from this idealization is a bit unfortunate but we take care of it in terms of a small perturbation. This is an example of an ideal picture that a physicist uses as a paradigm. On the other hand, a metallurgist, confronted as he is with *actual* metals, has his own paradigms. As I understand it now having come here, they mostly have to do with dislocations (which, I believe, live, multiply, climb, pile up and even die!). This is very nice. It is not necessary that dislocations exist; it is enough if they exist as paradigms! For example, quarks most probably do not exist but it is quite convenient to explain all matter in terms of quarks; it is a good mental picture. On the other hand, if we are going to discuss heavily deformed materials, is this paradigm based on dislocation as an elementary object convenient? True there are pictures showing dislocation— they are real objects and they certainly exist. We can even work out the mathematics of a single dislocation— no problem. I am told the two-body problem also can be done. But what if we have more than two, say 10, 20 or 10^{11}? That is where the problem lies. Near a large-angle grain boundary, do they retain their imitable integrity or not? If they don't, then we may have to look for something else in terms of which to describe these structures. Prof. Ranganathan did this by resolving the large deformation at the grain boundaries into a big part (DSC) plus a small part (described in terms of dislocation with Burger's vector taken from the DSC). I am happy with this picture. However, a doubt remains in my mind. In a metal, the large deformations at the grain boundaries must surely be sensed and felt by the electrons. If so, are we justified in ignoring the reactions of the electrons to such a heavy distortion? Even geometrically speaking, one wonders whether the dislocation concept is appropriate at a large angle grain boundary where there is such a pile up. Perhaps things are too amorphous-like in that region, and some alternate description should be tried (if not already done). So, the large-angle grain boundary appears to be a problem which physicists would be interested in because this is a case where one paradigm might give way to another.

Aside from this, there is a nontechnical matter that I raise on behalf of Prof. Ramakrishnan, which is: Where do we go from here? We obviously cannot meet time and again just to review work already available in books and journals. The important question is: Are we sure that there are sufficiently important, interesting, nontrivial open problems which physicists would be interested in? As of now, most of us physicists are *not* working on problems of mechanical behaviour. We are looking for the possibility of Discussion Meeting induced transitions. For something worthwhile to emerge, physicists must be willing to give more than 10% of their time. This is a practical issue if we mean business, and I suppose we do!

Prof. Joshi: Thank you Prof. Kumar. I now invite comments from the floor. Comments may please be restricted to broad issues or questions rather than matters of specific detail.

Dr G Venkataraman: As mentioned by you Prof. Joshi, I would like to make a few broad suggestions. The first of these arises out of a conversation I had with Prof. Ramaseshan at the time when the idea for the present Meeting took shape. Prof. Ramaseshan pointed out that while holding a meeting of this type was fine, everyone would go back and continue working on the same problems as before, instead of exploring the new grounds revealed at the Meeting. He emphasized that if fresh ground is to be broken, it would essentially have to be by young people who have not yet committed themselves to working in an already established area. I have been discussing this question informally during the last three days with several people, and the consensus appears to be that we must organize a regular, pedagogic school wherein young people can be given a systematic introduction that will orient them for research in this area.

Next I would like to point out that the Department of Science and Technology (DST) has identified this subject as a Thrust Area. If good proposals concerning experimental or theoretical research are made to DST, I am sure funds would be forthcoming.

Lastly, as regards future Meetings of this type, my sampling seemed to reveal that: (i) Future Meetings are necessary, (ii) they should not be large, and (iii) the topic of the Meeting should be more specific say like fracture, physics of large deformations etc.

Prof. Joshi: If we look at the growth of the interaction between physicists and metallurgists (in this country), we notice that some of it originated right here at RRC. In this Meeting, we heard on the first day a description of some experiments on serrated yielding performed by Dr Rodriguez's group. A theory of serrated yielding was also presented by a physicist from RRC. Maybe the theory was not explicitly motivated by those experiments but the interactions between the Materials Science group and the Metallurgy group must have had some influence. Some catalytic agent is definitely needed to promote such interdisciplinary interaction, may be in the form of an official directive!

I was having a conversation with Prof. Kumar wherein he remarked that when we return from this Meeting, most of us will go back to doing what we were doing earlier! What we do is, I suppose, decided by many factors but the value system is a key one. If one wants to encourage such interaction, then one must attach a value to it. I suggest that physicists and metallurgists in multidisciplinary Institutes like, for example BARC, should experiment in investing some percentage of their time to interdisciplinary activity of this kind. The outcome of such experiments could perhaps be reported at the next Meeting whenever we have it.

Anyway, as far as this Meeting is concerned, it has been a very fruitful one though, as some comments both from the panel and the floor indicate, a few aspects could have been better. But this Meeting has certainly had its utility, and we shall take advantage of whatever we have learnt to augment this interaction.

Prof. Kumar: I just want to add something. When I came here, I had a little misgiving in the sense that the subject obviously is an old one. I was aware that eminent physicists like Sir Charles Frank had worked on the subject. The point is that I had a feeling that around the World there must be many physicists working on metallurgy. Now as a physicist, I am not directly involved in this type of work and therefore I just don't know what has already been done. Unfortunately, no one here explicitly pointed that out, and also what has *not* been done. As someone remarked, the natives are not quite stupid! If we are not properly informed about what has already been done, we might end up reinventing the wheel!! Would someone like to comment?

Dr R Ramaswamy: I want to say a few things—probably in repetition, and some of them platitudinous perhaps! When a person like me comes to a Meeting like this, he does not necessarily come looking for problems. One comes, one listens to the problems aired, one says what one can, and one contributes. In that sense, I don't think it is valuable for us to seek where we are going *vis-a-vis* conferences of this type because such a conference serves precisely the purpose for which it was arranged *i.e.* to bring together people of different disciplines and see what each one can get out of it. *Of course* we will go back to doing whatever we were doing before. The hope is that the little one might have heard might make *the* difference. Undoubtedly there will be more conferences of this type in the future but whether they should be held or not are spontaneous questions. When Deepak and I go back to TIFR we might well say, "Why are we doing abstract problems? Let us get together with chemists etc". In that case we are the ones who would have benefited. One cannot induce such things; they happen reasonably spontaneously.

Prof. C K Majumdar: When I came here, I certainly did so with the purpose of hearing metallurgists because we physicists do not often hear people of other disciplines. It was certainly educative. The things learnt should not be viewed in terms of immediate return alone because they also broaden your outlook. Even if you go back to doing what you were doing before, your view point would have changed a little and that is a good thing.

Turning to specific suggestions, I think we should have another such Meeting, perhaps in three years. Time scales are a bit long in this country, and probably, it will be at least three years before we can really talk anything new— by new I mean results obtained in *our* laboratories.

Now there are not many places where interdisciplinary work of this type is being done. I for one do not even know where metallurgical work goes on, apart from organizations like RRC, BARC, HAL and the IIT's. Obviously there must be other organizations using at least some metallurgical skills, the State Transport Corporations for example. Judging from the conditions of the buses they ply, there is clearly scope for some technological improvement (!) which could perhaps be done by metallurgists. At the same time, the wayside auto shops seem to manage alright, and they appear to be having a way of accumulating empirical knowledge that is beneficial to their work. In all the training we talk about, we should not forget such people. Somehow they have to be exposed to modern developments. In other countries this is taken care of, and phenomena like exoemission are actually put to practical use by high-technology companies like Lockheed. Details of such applications are often not discussed in the open literature and we have to learn them on our own. History in fact shows that advanced civilizations often keep technology to themselves and do not allow it to percolate to other civilizations. In such cases therefore, we have to learn the hard way.

Not everything in science should be done just for publication or priority. Certain things, even if it means repetition, *have* to be done to make Society run better. Repetition may not actually be a bad thing for in the process one might actually improve on what is already known. I can give you an example. The Chinese apparently had ice cream long before the Europeans knew about it. Marco Polo brought ice cream knowhow from China to Europe, and later the Americans improved it! In short, there are aspects of technology which we have to develop on our own. In that sense, we should find a way of inducing some technologists also to attend such Meetings in the future.

The other thing I would like to comment on is the School that Dr. Venkataraman mentioned. The School should not just involve lectures alone; the students must also get exposed to some experiments. In that case, I think the School should be organized in places like this (RRC) or at the Indian Institute of Science, where there are appropriate facilities.

Dr K R Rao: My comments relate to the remarks made earlier by Prof. Kumar. I think many of us would like to go back and actually do something different instead of continuing to do the same thing we have been doing for the last 25 years or so. In this context, I think the identification of unsolved problems is very important. One example comes to mind and that relates to Atomic Data for Fusion Research prepared by the IAEA about four years ago. A huge report has been written identifying hundreds of problems. IAEA has followed up this effort with some funding, and has also been evaluating the data coming out of the various research Centres. Although we are not trying anything on that scale, I feel that if problems are identified and made known say through the Proceedings of this Meeting, it might lead to various people (including those not present here) picking up the strands. Particularly in the experimental field, there is no reason why some of us cannot try something new, provided new experiments or problems are identified by specialists.

Prof. V Balakrishnan: I wish to comment briefly on a point raised yesterday by Prof. Ramakrishnan. In his characteristic fashion, Prof. Ramakrishnan pointed out that it would be useful for solid state physicists to learn the basics of physical and mechanical metallurgy. This is being done in some places but perhaps the exercise could be made more systematic. It is certainly being done with respect to courses on materials science but not so much in the case of solid state physics. As far as the latter is concerned, if one can spend a lot of time on electronic properties then surely a chapter of mechanical properties is reasonable, especially as it will at least get the jargon straightened out for condensed matter physicists. This chapter need not be very long. I noticed that right here on the first day, many physicists expressed to me their concern about the jargon. They could not understand it, but repeated use of the term dislocation seems to have made it familiar enough to most people (rather like the way theorems are established in high energy physics, namely you repeat it often enough and it becomes a theorem)!

In a slightly more serious vein, I think that some simple experiments on mechanical behaviour should also be introduced in the undergraduate curriculum. And there are very dramatic experiments, like the one on work-hardening demonstrated by Bragg in his Royal Institution lectures. A similar one, perhaps already known to some of you, involves closing one end of an open cylinder with a tissue paper, filling it with sand, after which you put a metal rod and apply enormous load on it. We got this set up at IIT recently and I personally along with several other people put my full weight on the rod and the tissue paper did not break because the stress was distributed by those fine grains of sand. Experiments like this bring out beautifully the effect of interfaces, grain boundaries and so on. Perhaps we should spend some time generating ideas for such elementary but very effective demonstrations which will convey to physicists the basic concepts of metallurgy.

Dr R Chidambaram: I think what was unique about this Meeting was that it brought a small group of metallurgists and physicists together. Also, unlike other meetings where people come and either give invited talks or present contributed papers, I got the impression that one was expected in this Meeting to talk about problems one had not completely finished or one did not know enough about. Thus, for example, I did not talk about our work on the equation of state— something we know how to handle. Instead, I talked on something in which we had some doubts and in which some metallurgical concepts were involved. If you look at the matrix element which Dr Sahni was talking about, the value of that matrix element must be obtained, I think, by integrating over the personal responses from all the individual participants, as is being done here during the present Panel Discussion. With this in mind, I will tell you what I personally gained from this Meeting. Honestly, I did not expect that the metallurgists would ask the kind of questions they actually asked after my talk. Of course Dr Majumdar raised a point about the entropy equation which I had not written down. If one knew how to write it down, the problem of the structure of the shock front would be solved substantially, but the current state of the art is such that one does not know how to discuss entropy production in the case of shock propagation in solids. On the other hand, after listening to the large number of talks we had on dislocations and grain boundaries, I think I now have a better perspective on how to think about these physically, in relation to the propagation of a shock front. That way I think this Meeting has been very successful.

As regards the periodicity of such Meetings, I think a Meeting once in three years as Dr Majumdar suggested would be appropriate. And that should be interspersed with a School in which there are lectures both by physicists (theoretical as well as experimental) and metallurgists.

Prof. Joshi: Would a metallurgist from the floor like to react? Yes Dr Rodriguez.

Dr P Rodriguez: I would like to make a few observations and the first of these relates to Prof. Ramakrishnan's remark that before physicists deal with the real physical nature of problems in complex materials like alloys, they need to develop a better understanding of the basics of physical and mechanical metallurgy. As history shows, metallurgy has been enriched considerably by the work of the physicists, and in fact many physicists have contributed to the study of plastic deformation and the fracture of metals. For example there is the monumental work of Schmidt and Bose on the deformation behaviour of single crystals of fcc metals. Prof. Ramakrishnan showed a picture of such deformation behaviour, and quoting from Bell's work said that metallurgists ignore it but that is really first-year text book material for metallurgist! We start with the deformation behaviour of a fcc single crystal and then extend it to the polycrystal. That is my first point.

People have quoted many things, the old testaments, their heroes, etc!. I will quote George Santayana who said that those who do not learn history will be condemned to repeat it. So let us be careful about not repeating history! Particularly from some theoretical physicists, I got the impression that they would like to apply some newly discovered mathematical formalisms to explain already explained phenomena. I am not stating this as a criticism but it is important that before going ahead with applying a theory or a model one should take stock of the state of the art. This point was made by Prof. Kumar and it is important. One way of achieving this is to organize a course or even write a text book. We have beautiful books on physics for engineers, physics for metallurgists etc. May be it is time to write a book on metallurgy for physicists!

Another aspect that I would like to point out is that in the important area of deformation and fracture behaviour of materials, we have reached a stage of understanding wherein we can now *a priori* design an alloy. This topic, *i.e.* the relationship between microstructure and mechanical properties of alloys has been completely left out from this Discussion Meeting. By microstructure I mean the substructure for example, the distribution of second phases, their morphology, the dislocation density etc. We find that the total dislocation density *per se* is not always the controlling factor, rather the way the dislocations are arranged, *i.e.* whether they are tangled or have a cell-structure. This topic has been completely overlooked. Of course it is obvious that all topics could not have been covered in a Discussion Meeting like this. But this argument shows that there is enough scope to have more frequent Meetings, focussing attention on such specific topics.

Prof. Joshi: Since there is a time restriction, I am afraid I have to interrupt and cut short this interesting Discussion!

I will sum up by saying that there is a need for future Discussion Meetings as well as a tutorial School. The duration, the periodicity, the organization, the themes—all these could be left open at the moment.

Being the last speaker permit me to express our grateful thanks to the Organizers of this unique Meeting. I would also like to express our special thanks to our hosts who have taken such good care of us. Finally, I wish to thank the panelists, those who participated from the floor, and the audience in general for making this discussion lively. Thank you all once again!