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73-1262

Reprinted from: METALLURGICAL EFFECTS AT HIGH STRAIN RATES
Edited by R. W. Rohde, B. M. Butcher,
J. R. Holland, and C. H. Karnes
Book available from: Plenum Publishing Corporation
227 West 17th Street, New York, N.Y. 10011

PROBLEMS IN SHOCK WAVE RESEARCH

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I. HISTORICAL REVIEW

Theoretical studies of shock waves, their structure and their propagation date well back into the 19th century. Poisson, Stokes and Earnshaw were early pioneers; Rankine, the great Scottish engineer, and a less reknowned French scientist, H. Hugoniot, established foundations which were later elaborated by Rayleigh,[1] G. I. Taylor,[2] and P. Duhem.[3] Their work, along with more recent contributions by Bethe,[4] von Neuman,[5] Gilbarg,[6] R. Courant and K. O. Friedrichs[7] and others, has been adapted to solids in recent years[8] and serves us well today for most purposes. Recent developments by G. R. Fowles and R. Williams[9] promise a new dimension in the interpretation of experiments in solids, but fulfillment of their promise may await new measuring techniques.

Early experiments on the shock waves produced by projectiles in air were done by Ernst Mach,[10] who established a tradition for the use of high speed optics which has been carried on by Cranz and Schardin,[11] Walsh,[12] Fowles[13] and others. Consideration of the problems of supersonic aircraft gave impetus to the study of air shocks before and after WWII (Howarth[14]), and since 1950 there has been detailed and extensive study of shocks in gaseous plasmas.[15,16]

Modern developments in the study of shock waves in solids really arise from the Manhattan Project during World War II. Details of this period are lost in files of the Atomic Energy Commission and in the memories of various individuals. However, we do know that in this time and place it was realized that the jump conditions could be used to obtain pressure-volume relations, that experimental techniques for producing and measuring plane shock waves from explosives were developed, and that in the years following World War II a series of pioneering papers on this subject came out of Los Alamos.[12,17-19] Work done there also provided a frame and foundation for studies of elastic precursors and phase transitions, which have occupied so much of our energies during the last fifteen to eighteen years.

Progress in shock wave physics has been strongly tied to developments of experimental techniques. Los Alamos studies were initially largely made with pins used to record free surface motion. The use of these was highly developed by Stanley Minshall,[17] but they have been supplanted by flash gaps, initially developed by Walsh,[12] which are still widely used for pressure-volume measurements above 100 kbars. As interest developed in the detailed structure of shock waves, it also turned toward lower pressures and more refined recording methods. Optical level techniques developed by Fowles[13] and Doran[20] at Stanford Research Institute provided sensitivity for measurements at low pressures and quasi-continuous records of free surface motion. A condensor microphone method developed by Taylor and Rice of Los Alamos[71] offered significant improvement in time resolution, and an electromagnetic procedure used by Fritz and Morgan[72] has recently produced records of high resolution. Major steps forward were provided by Sandia Laboratories: first in Lundergan's development of the gas gun for impact studies[21,22] and then in development of the quartz gauge by Neilson, Benedick, Brooks, Graham and Anderson[23] and the laser interferometer by Lynn Barker.[24,25] These combined developments have led to resolution times of one to five nanoseconds in shock structure measurements below forty kilobars and to sharply enhanced abilities to evaluate theoretical models of material behavior. In a somewhat different class are the electromagnetic velocity gauge invented by E. K. Zavoiskii of the USSR[26] and the manganin gauge first developed by Keough and Bernstein at Stanford Research Institute.[27] These are gauges to be imbedded in a sample. They will probably never compete with quartz gauge and laser interferometer for time resolution, but they can be used to much higher pressures and can reduce problems of impedance mismatch. The potential of neither, nor of their various offspring, has yet been realized.

It has turned out that mechanical measurements yielding pressure-volume relations, precursor structure and phase transitions have been relatively easy to do. Electric, magnetic and optical measurements are much harder, though many have been done and some have been done well.[28] Still, the possibilities for research in this area are great, and, as mechanical measurements become harder, more attention will probably be directed toward these problems.

High speed computing machines play a particularly significant role in shock wave research. Without them one is constrained to consider shocks as discontinuities and to give minimum attention to details of shock structure between the discontinuities. Shock problems are relatively easy to solve numerically, and with high speed machines there is no barrier except cost to the most detailed comparison of shock structure with the predictions of various models. In this way extremely critical tests of theories of constitutive relations are possible.[29] Some use has been made of this capability, but its use is still limited--perhaps primarily by the scarcity of good physical models.

II. ACHIEVEMENTS

In 1963 Fowles and I attempted to collect references to all Hugoniot data that had been published and we found measurements on about eighty substances, not counting minor variations in composition of steel and aluminum.[30] In 1967 the Lawrence Livermore Laboratory issued a three volume, looseleaf compendium of shock wave data which contains entries for about 160 materials, with the same restrictions.[31] I doubt that the pace of data production has slackened; linear extrapolation from these two points suggests that the number of substances for which data are available today is about 300. Collection and publication of such data provides a real service to the technical community. The data are expensive to obtain and not easy to duplicate without special facilities. They should be made available to the general user.

In spite of the amount of data available, it turns out that few substances are well characterized over a large range of pressure. From the jump conditions one finds that the r.m.s. errors in pressure and compression in terms of particle velocity u and shock velocity D are

$$\delta p/p = [(\delta u/u)^2 + (\delta D/D)^2]^{1/2} = \delta(\Delta V/Vo)/(\Delta V/Vo)$$

Variations in arrival times of the shock over a free surface in the average experiment is probably not less than 50 nanosec over a 3 cm diameter specimen. If total travel time through the specimen is two microsec., the uncertainty in D is $\delta D/D \sim .05/2 = 0.025$. Measurements of u are probably better than this on the average, so the uncertainty in p and $\Delta V/Vo$ in the average published data point is probably 2.5 to 3%. It can be much more unless the work is done carefully. It can be appreciably less if the work is painstaking. As more measurements are published for a given material, one may expect the error in the mean Hugoniot curve to diminish.

The existence of good Hugoniot data on many materials has prompted much study of theoretical equations of state with the result that keener understanding of the compression process now exists, particularly for the rare earths and rare gases.[32]

In 1968 Jones and Graham published a table of elastic precursor measurements.[33] There were a hundred and thirty published measurements at that time, including duplicates and measurements on twenty different iron and steel alloys. The total has increased substantially since then, and it includes extensive series of precursor measurements in LiF made by J. Asay[34] and Y. Gupta.[35] As it presently stands, it is established that elastic precursors are indeed elastic waves. Their amplitude is directly related to the resolved shear stress which the material is supporting at the instant of measurement, and this amplitude decays as the wave propagates into the sample. The rate of decay is related to the dynamic failure of the material, and, in ductile materials, it can probably be related to the velocity and rate of generation of dislocations in the material, though this last statement must be labelled speculation at present. With some adjustment of parameters, a reasonable dislocation model can be used to fit most, but not all, of the measured shock profiles. Precursor decay measurements and the associated dislocation analysis have been made in lithium fluoride, tungsten, iron and aluminum, but not in other materials. Measurements at three different crystal orientations in tungsten strongly suggest that the slip mechanisms operating in shock loading are the same as those operating in quasistatic slip.[36] Electron transmission micrographs from recovered metal specimens suggest that the details of dislocation behavior in shocked materials may be quite different from those found in thin bar experiments, perhaps because of the very short distances travelled by dislocations during the shock process.[37]

In 1954 Stanley Minshall reported a 130 kbar "plastic wave" in iron which he tentatively identified as being due to a polymorphic phase transition induced by shock waves.[38] He tentatively identified this as the α-γ transition, but in a brilliant series of experiments which traced out the phase diagram in iron it was determined in 1961 to be a new phase,[39] later identified as hcp.[40] Since 1954 quite a number of solids have been found to undergo phase transitions under the influence of shock waves.[41] Shock transition pressure does not usually exceed the static pressure of transition, where static values are known. This is curious because the time available for transition is small and, since transitions are sometimes slow in occurring under static conditions, it might reasonably be assumed that they might not occur at all in a very short time, or that they might occur at higher pressures. This suggests that a study of the kinetics of phase transition under shock conditions may be fruitful. Calculations indicated that a finite transition rate produces a decaying wave similar to the elastic precursor resulting from dynamic failure[42] and that, if transition time is between 10^{-8} and 10^{-5} seconds, it can be detected in a shock experiment.

In a recent series of experiments on potassium chloride, D. B. Hayes has obtained results which tend to heighten the puzzle, rather than resolve it.[43] He has found that the kinetic behavior depends on crystal orientation. When the shock propagates along the <100> direction, the material transforms to a new and metastable phase or partially transforms to the CsCl structure in less than 10^{-8} seconds. He finds some evidence of slower decay from this intermediate state to some undefined state. When the shock propagates in the <111> direction, transition is slower, the transition time being 10 to 40 nanosec, depending on driving pressure, but the final state reached after this time is the well known CsCl state. There is no evidence of a transition state as found for the <100> orientation. The transition pressure determined from his experiments may be higher than the static pressure by about a kilobar, but this difference may be due to uncertainties in both static and shock experiments.

Effects of shock waves on magnetic materials has been of both practical and theoretical interest. Three processes have been identified as being responsible for producing demagnetization of magnetic materials by passage of shock waves. One is depression of the Curie temperature by compression. This occurs in iron-nickel alloys with nickel content greater than 30%. A second is transformation from a ferromagnetic to a non-magnetic state through a first-order phase transition. This is observed in iron when it changes from fcc to hcp at 130 kilobars. The third is anisotropic demagnetization, a kind of inverse magnetostriction resulting from rotation of the magnetic momentic vector when elastic strain is imposed on the lattice. This last effect occurs in nickel ferrite, yttrium-iron-garnet, manganese-zinc ferrite and other ceramic materials. It turned out to be rather complicated and has been resolved by elegant theoretical and experimental developments.[44-47]

Electrical measurements to determine the effects of shock compression on resistivity have been made for a number of materials.[28] The combination of geometric requirements, shock reflection problems and electronic response times make such measurements very difficult. Quite good measurements have been made in xenon, argon, carbon tetrachloride, germanium, iron, manganin and copper. Those in liquids were helpful in elucidating certain anomalies in the equations of state.[48] Measurements on germanium in the range of elastic compression were the basis for a detailed evaluation of band structure parameters, indicating that uniaxial compression is a valuable adjunct to hydrostatic compression for such studies.[49] Resistivity of iron shows some curious anomalies below 100 kilobars which have yet to be explained, and that of copper is anomalously high when compared with static compression measurements.[48,50] A substantial number of resistivity measurements have been made on alkali halides for the purpose of studying the collapse of the electron energy band gap under compression. The results are ambiguous, but enough information is obtained to show that shock resistivity experiments can provide valuable information in this area.[28,51]

An isolated but striking result which has dramatic implications for future research is the production of x-ray diffraction patterns in the vicinity of or behind the shock front. This technique was developed with LiF as specimen material. Its recent application to boron nitride[52] suggests that it may become an effective tool for structural studies.

III. PROBLEMS FOR FUTURE STUDY

Much is to be done, of course, in digesting past work, making it available in a synthesized form for others, and developing its physical implications. This is particularly true in measurements of pressure-volume relations. There are at least two approaches to the problem of determining an equation of state from shock experiments. One is strictly thermodynamic. Shock experiments provide data on a single curve in p,V,E space. Supplemental experiments are then required to provide off-Hugoniot and thermal data. Various methods for doing this have been tried and have not been very successful.[53-56] The situation will be improved if bulk sound velocities and temperatures can be measured in the shocked state, but it is unlikely that a complete thermodynamic characterization of any material will be achieved without reference to physical models. A second approach, and the one most used to date, is to assume a rough physical model for the substance, derive the equation of state, including undetermined parameters, and use shock wave data to determine the parameters. This procedure can be improved upon by combining thermodynamics and model in such a way that all thermodynamic data can be used in determining parameters of the equation of state.[57] This procedure is useful but is, in a sense, a stopgap. At the present time what is required is precise model development for restricted classes of materials based on elementary principles. These can then be combined with Hugoniot and/or other thermodynamic data to produce equations of state in which one can have reasonable confidence. The success of this procedure for special materials has been demonstrated by Ross, Pastine and others.[58-60] It is a demanding process, but it yields valuable results.

Careful study of dynamic failure is just beginning. Measurements of elastic precursor decay and shock structure for simple, pure, well-characterized and well-controlled single crystals are required. This must be coupled with the best micro-mechanical models available in order to determine the role played by various imperfections and atomic processes in dynamic failure under impact. When this is established, we may be in a position to predict dynamic failure in a material from ordinary laboratory measurements of yield stress, hardness, impurity content, etc. One thing that is needed rather badly is satisfactory reconciliation of shock experiments and ordinary thin bar experiments. The latter are used to measure failure stresses at strain rates up to about 10^3/sec. The former are essentially stress relaxation experiments. If data from both kinds of experiments are reduced to a common form, we may gain significantly in understanding of the underlying processes of dynamic failure.

The above remarks are directed primarily toward failure of ductile solids by the yield process. Fracture is much less understood, but concepts of fracture in ductile materials developed by conventional metallurgical techniques[61] and shock wave methods[62] are converging on what seems to be a reasonable understanding. The failure of brittle materials under shock conditions is not at all understood. Two questions are outstanding, and their investigation will lead to some insight into the total process. One concerns the transition from brittle to ductile behavior, which apparently occurs in some materials under pressure, and the role it plays in failure under impact. The other concerns the apparent total collapse of the stress deviator in some brittle materials, of which quartz and sapphire are notable examples.[63] Inasmuch as ceramic materials are coming to play an increasing role in our society, brittle failure will be of increasing future importance. If we understand it under the extreme conditions of impact, we may come to understand it otherwise.

Geometric aspects of fracture and failure in shock experiments have been largely neglected. It is reasonable during the formulation of concepts to concentrate on plane geometry, but an important test of concepts so developed lies in their extension to other geometries. It is not too early to start designing and planning experiments with other than uniaxial strain.

Insofar as phase transitions are concerned, we know essentially nothing about the kinetics of transition under shock conditions. Comprehensive and searching experiments on well-defined materials of various classes are needed before we can even state the problems clearly. A very critical question here, of deep meaning for physical theory, is whether or not this fast transition can be understood by application of quasi-equilibrium statistics. The only feasible alternative seems to be large scale machine simulation of particle dynamics.

It is unlikely that electron behavior is significantly influenced by the dynamics of shock compression. Electrons in solids move too rapidly for that. But we can't be sure without further experiments and interpretations of experiments. Anomalies exist, as indicated earlier, and until they are resolved we don't know whether electrical effects are understood or not. The anomalous thermoelectric effect reported by several workers[64] is a good example of a large effect beyond that expected from static experiments. It has been suggested that this is an essentially dynamic effect, but the argument is not conclusive. Alkali halides deserve more study under optimum conditions. Independent variations of temperature and pressure have been attempted, but more work along such lines is required.

Absorption spectroscopy is a powerful tool for studying the internal structure of solids under static conditions. Time resolved spectroscopy is possible in shock experiments, but it has been little used. Experimental problems are formidable, but not apparently insoluble.[51] Used in conjunction with resistivity or shock polarization experiments, it may tell us a great deal about the internal states of shocked materials.

Almost all insulating materials produce electrical signals on being shocked. This is commonly called "shock polarization" or "charge release," depending on the nature of the material. The effects are significant theoretically and practically. Practically, because these signals are often unwanted in experimental systems and they can obscure or confuse the nature of wanted signals. Their theoretical significance follows from the inference that they indicate the occurrence of dramatic changes in electrical structure of the solid in the vicinity of the shock front. These effects are well-documented[65] and have been characterized phenomenologically, but little progress has been made toward developing atomic models.

Problems of yield, flow and fracture are probably of greatest interest to the group assembled here this week. Such problems can usually be expressed in terms of behavior of stress deviators in the field. Because the amount of energy that can be stored in elastic deformation is limited, these deviators stop increasing at some point in the loading process and we call this failure. Failure of this kind is associated with fracture or flow of the material. But at least one other situation appears to exist which can produce collapse of the stress deviators, at least in uniaxial strain. If a first order phase transition occurs a consequence of shock compression, it seems plausible that the new phase will form so as to reduce the energy of deformation as well as that of compression. Looked at macroscopically, one would say that the stress deviators had collapsed as a consequence of the transition. If the material had been on the verge of yield or fracture before transforming, no such failure is imminent after transition. It may then be possible for it to absorb additional deformation. An effect like this has been observed in CdS[66] and InSb,[33] so the speculation is not pointless. It is then reasonable to inquire what the material behavior is on being cycled through the transition and whether or not its ultimate strength is substantially modified. These are interesting questions because they may have significant applications in addition to their scientific implications.

IV. PROBLEMS OF APPLICATION

Most of the preceding remarks related to scientific questions having to do with shock waves. Many problems of application remain to be resolved. Technologists seem inclined to respect the principle that improved understanding of fundamental processes leads to better technology, but to ignore it in practice. This is done with good reason because technology has gone very far with little understanding and the road to better technology through better understanding is a long and tortuous one.

This seems to have been less true in shock wave problems than others, perhaps because of the precedent set in the Manhattan Project. Perhaps also because of the difficulty of a "cut and try" approach. So problems of application and science are not always far apart. There are, of course, continuing problems of major importance in weapons design and military defense, with which many of you are familiar. Progress is being slowly made in these areas and efforts along present lines will undoubtedly be continued.

There are other important applications. Explosive or impact welding is not understood, despite the fact that it is an important commercial enterprise. There is no continuum mechanical model which will predict the gross features of the bond. The first light of mechanical understanding may exist, but more is required.[67] Some of the qualitative metallurgical features can be rationalized, but there is, for example, no theory which tells us why apparent diffusion coefficients are so large. This feature is reminiscent of some early, rather poorly documented, observations which suggested that under some conditions carbon can be driven freely through an iron lattice. Is it possible for shock waves to differentially accelerate dissimilar atoms so that the usual barriers to diffusion are lowered?

Diamonds are being commercially produced by shock compression. They are not very large and the business may not be very profitable, but it exists and might be better if the transition process were understood. Some ideas exist,[68] but a great deal of work will be required to develop them. There may be other products sufficiently valuable for manufacture by shock methods, but the question has not been thoroughly explored.[70]

The hardening effects of shock waves on metals are still not understood, though they are frequently used. Understanding is intimately related to questions of dynamic failure and deformation, and therefore to the motion and creation of dislocations and other defects.[69] Commercial applications of these effects may provide additional motivation for understanding them.

Explosive or shock-actuated devices are frequently suggested and sometimes developed for engineering applications. They might include such items as one-shot electrical generators, timing devices and fast-acting valves. They may depend on changes in conductivity or interaction of waves with associated fracture and flow. Their development is usually very costly. Development of a quantitative engineering discipline soundly based on the known behavior of materials under shock conditions would accelerate such applications.

V. CLOSING REMARKS

Problems of shock wave propagation in solids involve continuum mechanics, thermodynamics and materials or solid state science, all interacting in a very intimate way. A great deal of progress has been made in sketching a framework of theoretical and experimental techniques within which it is possible to do meaningful, perhaps even revolutionary, experiments in solid state science. Within this framework many significant experiments have been done relating to mechanical, thermodynamic, electrical and magnetic properties of solids.

But in a deep sense the real science of shock waves in solids has hardly been touched. When nothing had been done, exploratory experiments were appropriate. Now what is needed is intensive study of problems chosen primarily for their scientific import, by specialists in materials and solid state science, using, where possible, established and reliable experimental procedures. When this becomes common, we shall begin to see the real significance of shock wave research.

ACKNOWLEDGMENT

This work was supported by the United States Air Force Office of Scientific Research Contract 71-2037A and National Science Foundation Grant Number GH 34650.

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