The Interaction of Plane Shock Waves and Rough Surfaces

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(Received June 5, 1952)

Shock tube experiments have been conducted to determine the effect of surface roughness on shock waves in nitrogen passing over the surface. Shock retardation was measured for a series of two- and three-dimensionally rough surfaces at shock strengths from $\xi=0.1$ to $\xi=0.9$. The first-order approximation was made that the volume between the positions of the shock wave, with and without the rough surface present, multiplied by the specific energy behind the undisturbed shock wave represented energy dissipated by the roughness. The space rate of energy dissipation is presented as a function of the average particle size of the rough surface. It is also shown that the curvature of the shock wave in the vicinity of the surface depends on the roughness of the surface, the length of roughness covered, and the strength of the shock wave. In addition, the hundreds of measurements of shock wave contours made in this investigation showed that there is a random fluctuation in the angle of incidence of the primary shock wave of 1/15°. This fluctuation is presumably caused by the details of the diaphragm rupture even though measurements were made 14 ft from the diaphragm in a shock tube with a 2×7 in. cross section.

I. INTRODUCTION

THIS investigation was undertaken in an effort to obtain quantitative information concerning the interaction of a shock wave and a rough surface. This type of shock wave interaction has not heretofore been investigated even though it is of importance in any treatment of shock wave attenuation. It is hoped that these experiments may suggest a model of this interaction which can be examined theoretically.

II. EXPERIMENTAL PROCEDURE

Since direct information about the interaction of a shock wave and a rough surface was desired, photographic observation of the interaction was superior to any indirect measurement. As a quantitative measure of the effect of the interaction, an attempt was made to correlate the curvature of the shock observed in the vicinity of the surface with shock strength and roughness. It was soon apparent, however, that shock curvature could not be described in terms of these variables alone. Therefore, the rate of energy dissipation by the surface was chosen as a measure of the effect of the interaction.

To a first approximation, the energy subtracted from the one-dimensional flow behind a shock wave is equal to the volume between the positions of the shock wave, with and without the rough surface present, multiplied by the energy density behind the shock, which can be determined from the work done on the flow by the piston which produces the shock wave. This energy is not necessarily dissipated instantly into heat. Some of it will appear as potential or compressional energy resulting from the high pressure regions in the vicinity of grains of roughness, and as kinetic energy of flow in a direction perpendicular to the motion of the primary shock. Nevertheless, this energy has been removed from the original flow field; and therefore, an attenuation of the primary shock wave must result.

The effect of a rough surface on a shock wave was observed by photographing a shock wave after it had passed over a limited length of controlled roughness. The shadowgraph method was used throughout this investigation. A representative photograph of this interaction is shown in Fig. 1. It was essential that a portion of the primary shock wave appearing in the photographs lie outside of the region of influence of the roughness in order to allow a comparison of disturbed and undisturbed shock waves. The theory and confirming experiments for the rate of growth of the region of influence of the roughness are discussed in Appendix A.

The rough surface itself was cemented to a sharpened plate bolted near the top of the shock tube. The plate was designed so that the transition from smooth plate to rough surface could be made as continuous as possible. A series of fine wires was fastened permanently within the field of view in order to provide reference lines for the determination of the position and shape of the primary shock wave.

The maximum, minimum, and average grain size of the sandpapers used in this investigation are shown in Table I. Actually two dimensions of the grains are as shown while the third is approximately 50 percent larger. Part of each grain is buried in the adhesive.

Sandpaper† was used throughout this investigation

TABLE I. Characteristics of various sandpapers used.

Designation	Max. Size $\times 10^{-3}$ in.	Av. Size $\times 10^{-3}$ in.	Min. Size $\times 10^{-3}$ in.
24–3	45.5	32.1	26.0
30–2½	37.5	27.8	21.5
36–2	30.5	23.2	16.5
40–1½	26.0	18.4	13.0
50–1	21.5	14.1	9.5
60–1/2	16.5	10.9	6.5
80–1/0	13.0	7.7	5.7
150–4/0	5.7	3.9	2.7
400–10/0	2.0	0.93	0.10

† The sandpaper used in this investigation was Production Paper supplied by the Minnesota Mining and Manufacturing Company, St. Paul, Minnesota. The technical information contained in Table I was furnished by Mr. Sidney L. Weichman of the Abrasive Laboratory, Minnesota Mining and Manufacturing Company.

* Now at Los Alamos Scientific Laboratory, Los Alamos, New Mexico.

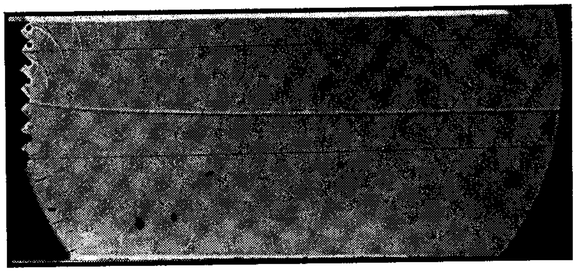

FIG. 1. A representative photograph of the interaction of a shock wave and a rough surface. The surface is a .100 in two-dimensional roughness, and the shock strength is $\xi=0.7$.

to provide a controlled three-dimensional roughness because of the uniformity and range of roughness of the available papers. Two-dimensional roughness was obtained by milling symmetric 90° sawteeth into gauge stock. The heights of the resultant right-triangular obstacles were 0.010 in., 0.040 in., 0.070 in., and 0.100 in.

III. MEASUREMENTS OF THE PHOTOGRAPHS

As mentioned above, all of the photographs of the shock wave-roughness interaction were taken near enough to the leading edge of the roughness to insure that part of the shock wave was outside of the region of influence of the roughness. It was therefore possible to determine the area between shock waves of a particular strength, one of which has passed over a rough surface and one of which has passed over a smooth plate, by superposing the undisturbed region of the two shocks. This superposition was made indirectly by measuring the distance between each of the shock waves and one of the bench wires at twenty-nine points five millimeters apart. These measurements were sufficient to determine the area "A" shown in Fig. 2. The difference between the areas "A" for shocks that have passed over rough and smooth surfaces, multiplied by the specific energy behind the undisturbed shock represents the energy degraded by the roughness per unit depth of flow.

IV. EFFECT OF EXPANSION CHAMBER PRESSURE

Nine values of shock strength were used in this investigation; ξ, the initial pressure divided by the pressure behind the shock wave, was varied from 0.9 to 0.1 in steps of 0.1. All of the shock waves were produced by using nitrogen in the expansion chamber and hydrogen in the compression chamber. In order to cover this range of shock strengths conveniently, it was necessary to vary the initial expansion chamber pressure from one atmosphere to approximately 1/30 of an atmosphere as determined from the Taub equation,[1] the fundamental shock tube equation relating initial pressure ratio across the diaphragm to the shock strength produced. When nitrogen and hydrogen are used in the chambers of a shock tube, the Taub equation becomes

$$p_0/p_2=\xi\{1-0.2727(1-\xi)[7\xi(6+\xi)]^{-\frac{1}{2}}\}^{6.878}. \quad (1)$$

The possibility that these variations in initial pressure, which caused a threefold variation in pressure behind the shock wave, might influence the results of the interaction was investigated by determining the area "A" for a shock strength $\xi=0.1$ and for a 0.100 in. two-dimensional roughness over a fourfold range of initial pressure. The results of this experiment are shown in Table II. It is apparent that this variation of initial pressure did not influence the interaction significantly. This result suggests that shock wave diffraction around the particles of the surface is more important in causing shock retardation than viscous dissipation in the flow behind the shock. This conclusion results from the following line of reasoning.

Under the conditions of this experiment the temperature behind the shock wave was held constant while the pressure was varied. The coefficient of viscosity is independent of pressure at constant temperature. Also, the velocity field produced by a shock wave depends primarily on the pressure ratio across the shock wave and not on the absolute value of the pressure. As a result the work done or energy dissipated by the viscous forces which is proportional to the coefficient of viscosity, the velocity gradients, velocity, and time will be independent of initial pressure. However, the energy density behind a shock wave is directly proportional to the initial

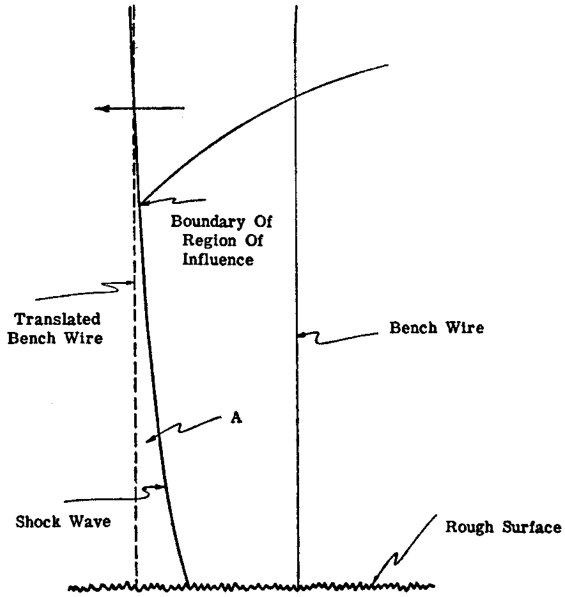

FIG. 2. Deformation of a shock wave caused by interaction with a rough surface.

[1] See F. W. Geiger and C. W. Mautz, *The Shock Tube as an Instrument for the Investigation of Transonic and Supersonic Flow Patterns* (Engineering Research Institute, University of Michigan, 1949).

pressure (see Eq. (2)). Therefore, if viscous forces were the primary cause of the energy dissipation observed, retardation area would be inversely proportional to the pressure. Since retardation area is independent of pressure, a different dissipation mechanism must be found. Multiple diffraction is a mechanism which is known to cause shock retardation and which should be dependent on shock pressure ratio and not on the absolute pressure.

V. DISTANCE CORRECTION

Small variations in initial expansion chamber pressure and room temperature combined with small uncertainties in the delay circuit and spark source timing insured that the shock wave did not appear in the same place relative to the roughness in every picture. In fact, there were twenty millimeters between the extreme acceptable locations. This distance was almost ten percent of the total useful length of the roughness. It was necessary, therefore, to apply a correction to the measured retardation area in order to make all measurements comparable.

TABLE II. The effect of initial pressure on retardation area produced by a 0.100 in two-dimensional rough surface. Each area reported is the average of two determinations.

Initial pressure (mm Hg)	Shock strength	Retardation area (sq mm)
14.2	0.1	256
24.0	0.1	272
45.2	0.1	261

The dependence of retardation on the length of roughness traversed was determined for number two sandpaper for three values of shock strength. A linear relation between net retardation area, the difference in area with and without the roughness present, and distance gives good agreement with the experimental data within the limited accuracy of the data as shown in Fig. 3. Therefore, a linear distance correction was applied to the experimentally determined net retardation areas. Thus, the rate of dissipation of energy appears to be independent of the length of roughness covered. This result also suggests that the primary mechanism of shock retardation is multiple diffraction since the shock retardation produced by each of the diffraction processes would be additive and independent of the length of roughness covered. On the other hand, if viscous forces caused the dissipation, one would expect the retardation area to depend quadratically on length, because the rate of dissipation of energy would be proportional to the length of roughness which had been covered at any given time.

VI. EXPERIMENTAL RESULTS

Curves of retardation area as a function of shock strength for number 1/0 and 2 sandpaper and for a smooth plate are presented in Fig. 4. Note that the shock is retarded quite significantly by a smooth plate. Presumably this retardation arises from viscous dissipation in the boundary layer behind the shock. All of the curves are forced to go to zero when $\xi = 1.0$. This restriction follows from the fact that the region of influence of a rough surface vanishes for a sound wave as shown in Appendix A. Similar results for all values of three dimensional roughness listed in Table I are summarized in Fig. 5, in which the net retardation area is plotted as a function of average grain size for different values of shock strength. Finally, the net area is translated into terms of the space rate of dissipation of energy by multiplying the area by the energy density behind

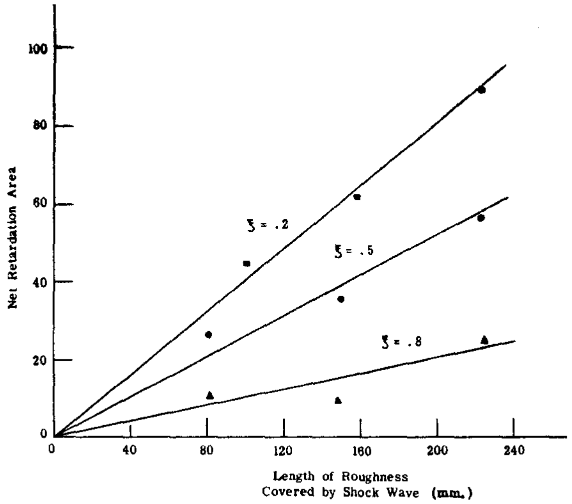

FIG. 3. The dependence of net retardation area on the length of roughness covered by a shock wave.

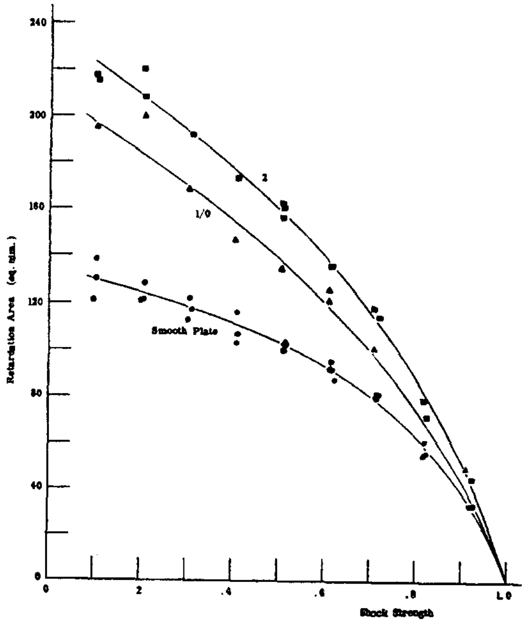

FIG. 4. Retardation area as a function of shock strength for number 1/0 and 2 sandpapers and for a smooth plate.

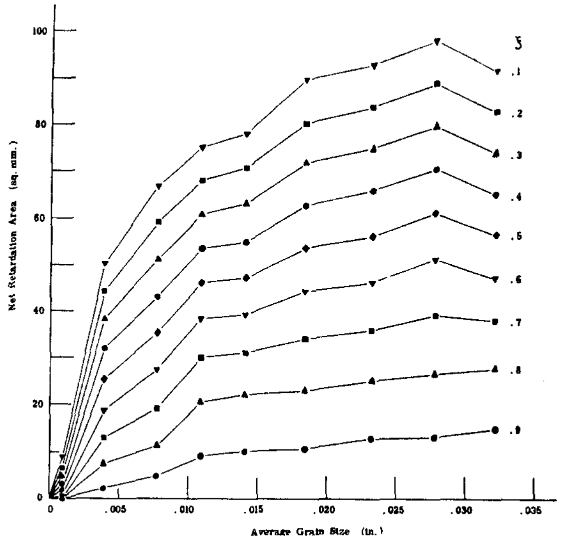

FIG. 5. Net retardation area as a function of shock strength for the three-dimensional rough surfaces listed in Table I.

the shock wave and dividing by the length of roughness covered. This energy density is[2]

$$\epsilon = p_0(\mu-1)(1-\xi)[\xi(1+\mu\xi)]^{-1}. \quad (2)$$

Figure 6 shows the final results for three-dimensional roughness. Net retardation area as a function of grain size and energy dissipation as a function of shock strength for two-dimensional roughness are similarly presented in Figs. 7 and 8.

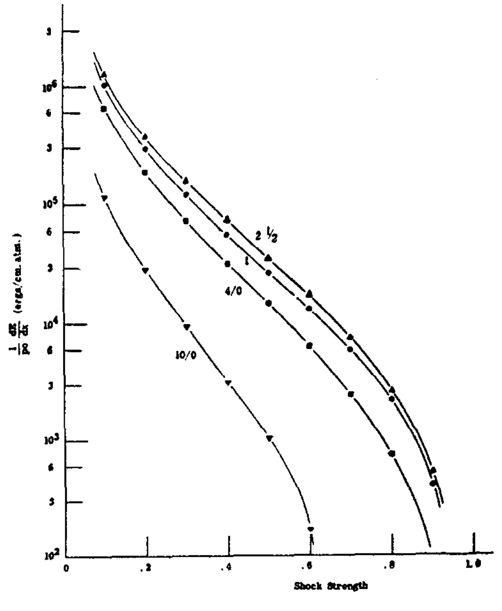

FIG. 6. The space rate of dissipation of energy per unit depth of flow for four values of three-dimensional roughness.

[2] C. W. Lampson, *Resumé of the Theory of Plane Shock and Adiabatic Waves with Applications to the Theory of the Shock Tube,* Ballistic Research Laboratory, BRL-TN-139.

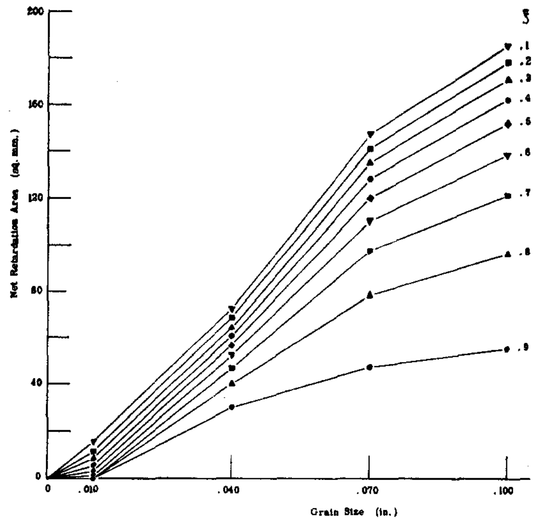

FIG. 7. Net retardation area as a function of shock strength for two-dimensional rough surfaces.

The curvature of a shock wave produced by a rough surface may be determined by measuring the distance between similar shocks photographed with and without roughness present. In this measurement special care must be used to correct for the random variation in the angle of incidence of the primary shock wave discussed in the next section. Figure 9 shows the shock curvature for shock strengths $\xi=0.1$, 0.5, and 0.9, and a number 2 sandpaper roughness. In each case the shock wave has covered approximately twenty-two centimeters of the surface. Note that the length of the curved portion of the shock wave varies with shock strength as predicted in Appendix A. The shock curvature for a strength of $\xi=0.2$ and a roughness of number 2 sand-

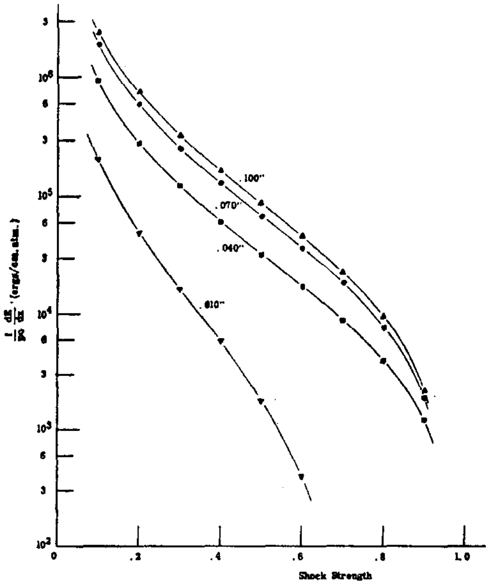

FIG. 8. The space rate of dissipation of energy per unit depth of flow for two-dimensional rough surfaces.

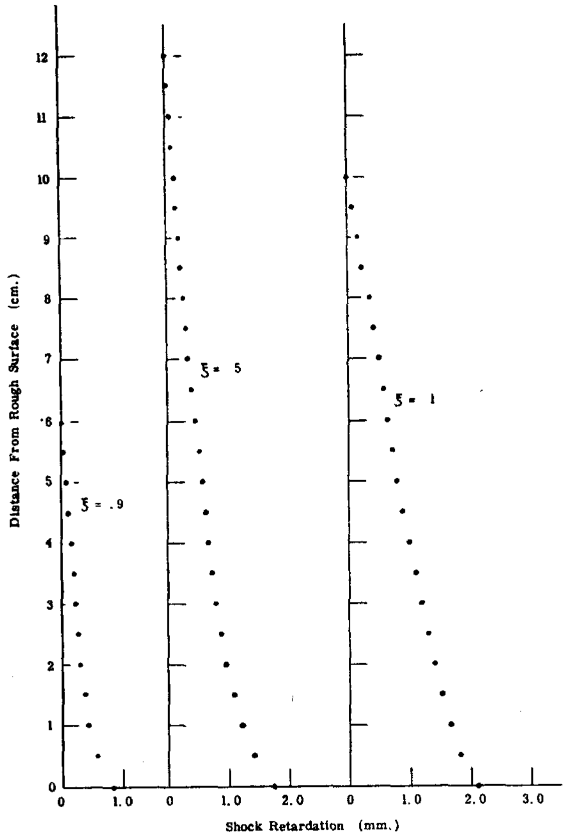

FIG. 9. Shock curvature produced by a number 2 sandpaper roughness for shock strengths of $\xi=0.1$, 0.5, and 0.9. In each case the shock has passed over approximately 22 cm of roughness.

paper is shown in Fig. 10. In this case the curvatures correspond to different lengths of roughness covered. Apparently the curvature of a shock wave produced by a rough surface is a function of shock strength, the grain size of the roughness, and the length of the roughness covered by the shock.

VII. SOURCES OF EXPERIMENTAL ERROR

The experimental results reported in the last section are subject to error from three sources. There are the usual uncertainties in measurement which influence the determination of the retardation area; there are electronic errors which influence the measurement of shock strength; and finally the shape of the primary tube shock was not reproducible from shot to shot. These factors shall be discussed in turn.

As mentioned earlier each experimental point of the dissipation area curves was determined from a set of twenty-nine measurements of the distance between the shock wave and a bench wire. These measurements were made with a Bausch and Lomb ×6 spectrographic magnifier. In thirty-five instances two independent measurements of dissipation area were made from the same photograph. The standard deviation of comparable measurements was 3.4 square millimeters.

The error in the determination of shock strength arising from systematic and random errors in the determination of shock transit time between two stations represents only a few parts per thousand and is therefore negligible with respect to other sources of error.

The most serious source of uncertainty in this experiment arises from the lack of reproducibility of the primary tube shock. It has been found that shock waves produced in one shock tube with identical pressure ratios across the diaphragm are not necessarily identical. This fact was first noticed by Smith.[3] Likewise, in his investigation of Mach reflection, Bleakney[4] has noticed a random variation in the angle of incidence of the primary shock wave. Similar results have been observed in this investigation. The average variation in the angle of incidence of the primary shock was 1/15°. However, for strong shocks the variation of the angle of incidence was sometimes much greater.

Presumably the details of the diaphragm rupture can influence the shape of the primary shock wave at an observation station separated from the diaphragm by a distance of more than twenty-four times the largest

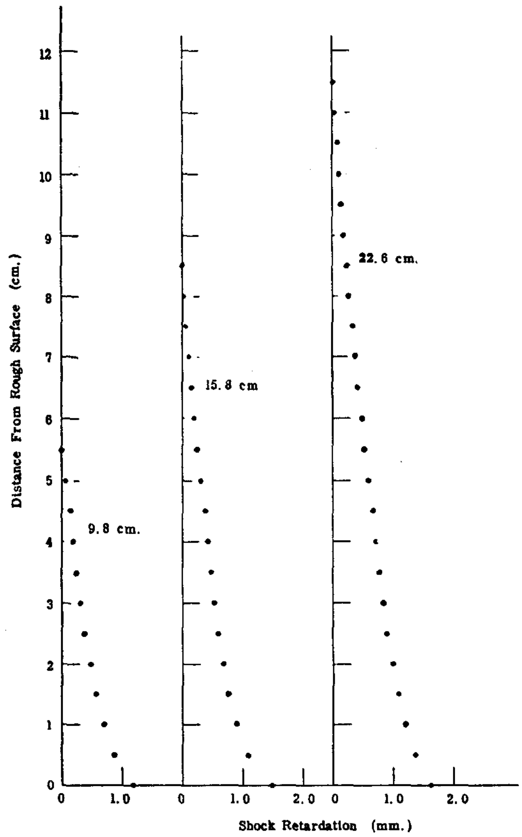

FIG. 10. Shock curvature produced by a number 2 sandpaper roughness for a shock strength of $\xi=0.2$. The three curvatures shown correspond to different lengths of roughness covered.

[3] L. G. Smith, *Photographic Investigation of the Reflection of Plane Shocks in Air*, OSRD-6271.

[4] Walker Bleakney, private communication.

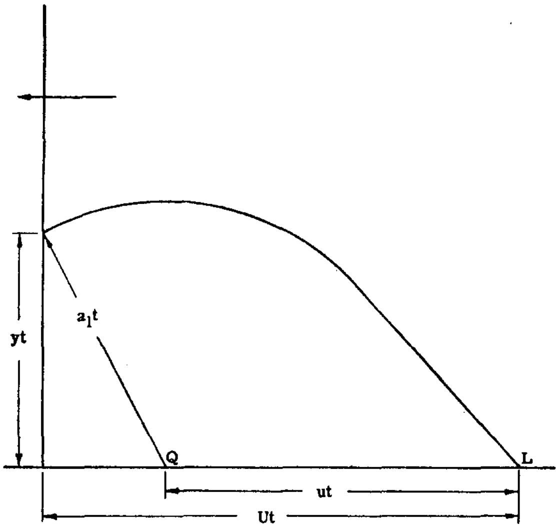

FIG. 11. The growth of the region of influence of an infinitesimal line disturbance behind a shock wave.

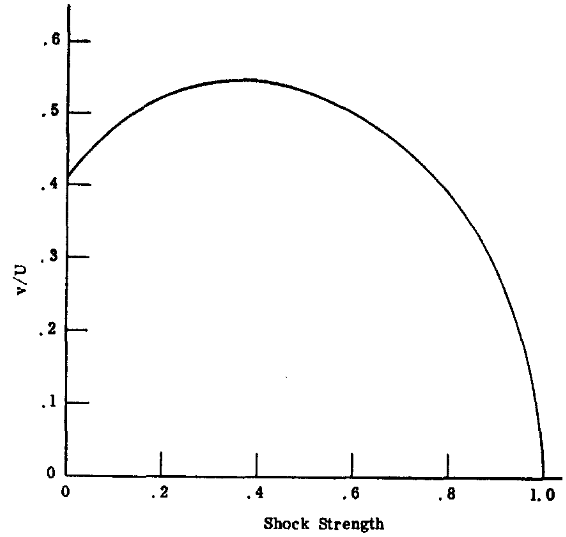

FIG. 12. The ratio of the rate of growth of the region of influence of a line disturbance along a shock wave to the velocity of the shock wave as a function of shock strength.

dimension of the tube. The Michigan shock tube has a 2×7 in. cross section and the test section is 14 ft from the diaphragm. This random variation in the shape of the primary shock should be considered in any investigation requiring precise knowledge of the shock contour.

A simple analysis shows that the error introduced into an area determination by an inclination of the primary shock is $(a+b)a\theta/2$, where a and b refer, respectively, to the distances inside and outside of the region of influence of the roughness and θ is the angle of inclination of the shock wave. This represents an uncertainty in the retardation area of 7 square millimeters in a representative case. From these considerations it follows that the uncertainty in the determination of a retardation area is approximately 8 square millimeters. Unfortunately, this uncertainty is relatively large compared to the net retardation area itself. Nevertheless, these experiments do demonstrate the essential features of the shock wave-roughness interaction.

APPENDIX A. GROWTH OF THE REGION OF INFLUENCE OF AN INFINITESIMAL DISTURBANCE

The rate of growth of the region of influence of an infinitesimal disturbance may be determined by the following analysis. Consider a plane shock wave incident upon a line disturbance, L, of Fig. 11. After a time t, the shock has reached the position Ut. In the same time the gas particles initially at L have been swept downstream a distance ut to Q. Simultaneously, a sound wave with center at Q has propagated a distance a_1t out into the flow. Similarly sound waves have originated from the gas particles swept past L at later times. In the case of a supersonic flow behind the shock wave, the envelope of all these sound waves becomes the well-known Mach surface terminated in a section of a cylinder. For a subsonic flow the envelope is simply the initial cylinder since the sound waves starting at later times can never catch up with the original wave. In both cases this envelope encloses the region of the flow field that has been affected by conditions at L. The rate of growth of this region along the shock wave can be determined from the Pythagorean theorem.

Let y be the velocity, perpendicular to the direction of motion, of the intersection of the initial sound wave and the shock wave:

$$y=(a_1^2-(U-u)^2)^{\frac{1}{2}}.$$

By substituting values for the sound speed and shock and flow velocities in terms of shock strength, one obtains the following equation for the ratio of y to the shock velocity:

$$\frac{y}{U}=[\mu(1+\mu\xi)(1-\xi)]^{\frac{1}{2}}(\mu+\xi)^{-1}.$$

This relation is plotted in Fig. 12 for a diatomic gas with $\mu=(\gamma+1)/(\gamma-1)=6$. The velocity of the region of influence of the roughness relative to the velocity of the shock is a maximum for a shock strength slightly less than $\xi=0.4$. Thus, for this shock strength, the length of roughness that can be covered under the restriction that the intersection of the region of influence of the roughness and the shock wave be no more than 12.5 cm from the rough surface is 23 cm. For experimental convenience all of the pictures of the shock wave-roughness interaction were taken approximately 23 cm from the leading edge of the roughness.

The simple theory for the rate of growth of an infinitesimal disturbance has been verified directly. A one-eighth-inch square block was used to produce an observable peturbation. Such a block may be considered infinitesimal at distances large compared with its dimensions. Three pictures were taken with a shock strength of $\xi=0.4$ to determine the location of the region of influence along the shock wave at various times. In each case the predicted position agreed with that observed to within one millimeter. The region of influence of the block had moved up the primary shock wave 45, 70, and 123 millimeters in these three cases.

VIII. CONCLUSIONS

In an investigation of the effect of a rough surface upon a shock wave passing over it, it has been found that the shock wave is retarded in the vicinity of the surface. The angle between the shock and the surface is definitely less than 90°, but a Mach configuration does not develop. A quantitative measure of the shock wave-roughness interaction is provided by measurements of the space rate of dissipation of energy for nine values of shock strength ranging from $\xi=0.1$ to $\xi=0.9$ and for thirteen different surfaces. It is also shown that the curvature of the shock wave near the roughness depends on the shock strength, average grain size of the surface, and length of the surface covered.

This investigation brings to light the fact that the shape of the primary shock wave in a shock tube may vary measurably from shot to shot.

The author is deeply grateful to Mr. Robert N. Hollyer, Jr., who assisted in designing and conducting these experiments, and to Mr. Robert Kaiser, who measured the hundreds of photographs taken in this investigation. Financial support for this work was provided by ONR.

JOURNAL OF APPLIED PHYSICS VOLUME 23, NUMBER 12 DECEMBER, 1952

Neutron Diffraction Studies of Cold-Worked Brass*

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(Received July 14, 1952)

Powder diffraction data with neutrons have shown the integrated intensities to be identical in cold-worked (filed) and annealed brass with no trace of extinction effects. Long wavelength transmission studies have also shown that the diffuse scattering is increased by less than 0.4 percent upon severely cold rolling brass. A new technique of examining the Bragg discontinuities supports the hypothesis that the major part of the broadening is due to lattice distortion. Some remarks are presented concerning the analogy between long wavelength neutrons and conduction electrons with respect to scattering by dislocations. The effects of dislocations on coherent scattering are also considered.

THE Debye-Scherrer patterns of cold-worked metals have been studied for over a decade by many authors, but the observations have been at variance even in very recent work. While line broadening and changes in the integrated intensities of some or all diffraction lines have always been observed in cold worked powders, points of disagreement still exist. They are:

1. Is there any difference in the background of diffraction patterns of cold worked and annealed metals?
2. Are the integrated intensity differences entirely attributable to extinction?
3. Is the extinction primary or secondary?
4. Is the broadening due to lattice distortion or to particle size?

It is the purpose of this paper to present some neutron diffraction studies which attempt to answer questions 1, 2, and 4 by virtue of some unique properties of neutrons. We shall take up these questions in the order presented.

* Work carried out under contract with AEC.

1. DIFFUSE BACKGROUND

Reliable studies of the diffuse background have been made recently with Geiger counters.[1–4] Hall and Williamson[2] have reported about a 15 percent increase in diffuse background over the entire diffraction pattern in filed aluminum powder, whereas Averbach and Warren[1,3] find no difference to within ~2 percent between cold-worked and annealed samples of both brass and aluminum. In each case the diffuse background was measured in the region far from the Bragg peaks so that their broadening did not interfere with the measurement. Wagner and Kochendörfer[4] have found the diffuse background from highly deformed single crystals of Zn to be the same as that from undeformed crystals. They also find no change in the

[1] B. L. Averbach and B. E. Warren, J. Appl. Phys. **20**, 1066 (1949).
[2] W. H. Hall and G. K. Williamson, Proc. Phys. Soc. (London) **64B**, 937 (1950).
[3] McKeeham, Averbach and Warren, Phys. Rev. **86**, 656(A) (1952).
[4] G. Wagner and A. Kochendörfer, Ann. Physik **6**, 129 (1949).