15. F. Marconi, S. Rudman, and V. Calia, "One-dimensional unsteady two-phase flow with shock waves," AIAA Paper No. 1448 (1980).

INFLUENCE OF THE INITIAL CHARACTERISTICS OF THE MEDIUM ON THE PARAMETERS OF THE REFLECTION OF SHOCK WAVES

N. A. Kostyukov and G. E. Kuz'min

UDC 532.593

The passage of shock waves through solids can be accompanied by various physicochemical transformations. The results of a transformation depend on the change in the state of the medium under the shock-wave action, which is determined, in turn, not only by the intensity of the shock wave but also by the parameters of the initial state of the medium. The development of new phase transitions and chemical reactions [1-4], impact hardening of brittle alloys [5], the compression of solid and refractory powders [4, 6, 7], etc. become possible for certain combinations of the initial parameters.

Actual schemes of impact loading are such that the oblique reflection of shock waves from the interface between two media with different properties often occurs. In this connection it seems interesting to clarify how significant the influence of the change in the initial parameters of the medium on the reflection parameters may prove to be.

1. Statement of the Problem and Subjects of the Investigation

In the work we investigated only the region of regular regimes of reflection, since the flow structure in solids during irregular reflection has not yet been studied. In accordance with [8-10], the critical value of the angle of inclination of the incident wave at which the transition from the regular to the irregular regime of reflection occurs was taken as equal to the value for the upper limit of the region of existence of the regular regimes.

The paper is devoted to a numerical study of the influence of the initial characteristics of the medium and the loading parameters on the values of the critical angle φ^* and the pressure p_2 behind the reflected wave. In particular, the dependence of these parameters on the pressure p_1 in the incident wave and on the initial temperature T of the medium was studied in detail. In addition, we investigated the dependence of the pressure behind the reflected shock wave on the angle of incidence φ for different initial temperatures T. Data were obtained on the influence of the initial porosity of the metal on the value of the critical angle and on the pressure change during reflection.

Aluminum, copper, and tungsten were chosen as the subjects of the investigation. The choice was conditioned by the presence of reliable data on the equation of state in a wide region of variation of pressure and temperature; by the absence of phase transitions in the investigated region, allowing us to isolate in pure form the influence of the parameters of the initial state and to simplify the interpretation of the results obtained; by the considerable differences in the chosen media with respect to dynamic compressibility, initial density, and such parameters characterizing the change in the state of the substance under loading as the heat capacity and the volume expansion coefficient.

We consider the incidence of a plane shock wave AO onto a reflecting surface EF at an angle φ (Fig. 1). It is assumed that the boundary condition, consisting in the flow being parallel to the reflecting surface, can be satisfied by means of the reflected shock wave OB [11]. The flow in regions 0, 1, and 2 is assumed to be uniform, while the velocity of propagation of the shock wave AO relative to the undisturbed medium 0 is constant. The problem is analyzed in a coordinate system connected with the point O in which it is stationary.

2. Calculating Equations and Method of Solution

According to [11], the expression for the angle θ_1 of deviation of the stream by the incident shock wave has the form

Novosibirsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 1, pp. 121-125, January-February, 1985. Original article submitted October 28, 1983.

0021-8944/85/2601-0109$09.50

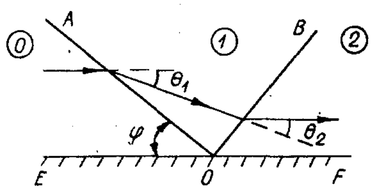

Fig. 1

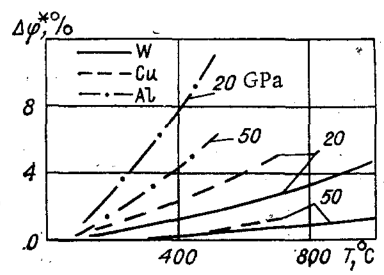

Fig. 2

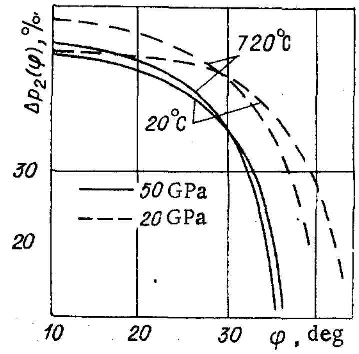

Fig. 3

$$\theta_1 = \varphi - \operatorname{arctg}(V_1 \operatorname{tg}\varphi / V_0), \tag{2.1}$$

where V_0 and V_1 are the specific volumes of the medium in regions 0 and 1, respectively. The specific volume V_0 at the temperature T can be found from the approximate expression

$$V_0 = V_{20}[1 + \beta_1(T - 20) + \beta_2(T - 20)^2]. \tag{2.2}$$

The values of the specific volume at T = 20°C (V_{20}), the coefficients β_1 and β_2, and the heat capacity C for the three investigated materials are presented in Table 1. The specific volume V_1 behind the incident shock wave is found from the Hugoniot adiabatic curve for the heated substance. If the substance obeys the Mie–Grüneisen equation of state and the variation of its internal energy with heating is described in the Debye approximation then, according to [12], the equation for the Hugoniot adiabatic curve for such a substance with allowance for heating has the form

$$p_1(V_1, T) = p_1(V_1, 20) + \frac{p_1(V_1, 20)(V - V_{20})/V_1 + 2C(T - 20)/V_1}{2/\gamma(V_1) + 1 - V_0/V_1}, \tag{2.3}$$

where $\gamma(V_1)$ is the Grüneisen parameter, which is assumed to be independent of temperature.

The functions $\gamma(V_1)$ and the Hugoniot adiabatic curves $p_1(V_1, 20)$ at T = 20°C were borrowed in tabular form from [13] for monolithic media and from [14-16] for porous media. The values of γ and p_1 at intermediate points were found by the method of cubic interpolation.

The angle θ_2 of deviation of the stream by the reflected shock wave is determined from the relation

$$\theta_2 = \nu - \operatorname{arctg}(V_2 \operatorname{tg}\nu / V_1), \tag{2.4}$$

where V_2 is the specific volume behind the reflected wave; ν is the angle between the direction of flow of the substance in region 1 and the front of the reflected wave. Using the laws of conservation of mass and momentum at the front of an oblique shock wave, we can write the following equation for the angle ν:

$$\sin^2\nu = \frac{[p_2(V_2, T)/p_1(V_1, T) - 1]/(V_0 - V_1)}{(V_1 - V_2)\left[1 + V_0^2/(V_1^2 \operatorname{tg}^2\varphi)\right]}, \tag{2.5}$$

where $p_2(V_2, T)$ is the pressure behind the front of the reflected wave. Neglecting electronic terms in the Mie–Grüneisen equation of state, which is permissible then temperatures are not too high, we can show that

$$p_2(V_2, T) = p_1(V_2, T) - \frac{p_1(V_2, T)(V_0 - V_1) - p_1(V_1, T)(V_0 - V_2)}{V_2[2/\gamma(V_2) + 1] - V_1}, \tag{2.6}$$

where $p_1(V_2, T)$ is the pressure required for the compression of the substance from the specific volume V_0 to V_2 by one shock wave. Consequently, the quantity $p_1(V_2, T)$ is determined from the single-compression adiabatic curve.

As the reflecting surface we consider an "absolutely rigid" barrier, for which the boundary condition has the form

$$\theta_1(\varphi, p_1, T) - \theta_2(\varphi, p_1, T, V_2) = 0. \tag{2.7}$$

The algorithm for determining the pressure $p_2(V_2, T)$ behind the reflected wave for given φ, p_1 and T consists of the following steps: V_0 is calculated from (2.2); after this V_1 is determined from (2.3), with $\gamma(V_1)$ and $p_1(V_1, 20°)$ being found by interpolation from tables;

TABLE 1

Material	V_{20}, m³/Mg	β_1, 10^{-6} deg^{-1}	β_2, 10^{-8} deg^{-1}	C, J/(g·deg)
Aluminum	0,369	67,8	29,40	0,90
Copper	0,112	50,1	2,16	0,39
Tungsten	0,052	12,9	0,43	0,14

θ_1 is calculated from (2.1); Eq. (2.7) is solved for V_2, with the values of $p_2(V_2, T)$, ν, and θ_2 being found from (2.6), (2.5), and (2.4), respectively. To solve Eq. (2.7) we use the method of division of a segment in halves, characterized by a sufficiently high convergence rate, simplicity, and the possibility of obtaining good accuracy. For values of the angle of incidence φ exceeding the critical value φ^*, Eq. (2.7) has no solutions. For $\varphi < \varphi^*$ Eq. (2.7) has two solutions, of which we chose, in accordance with [11], the solution corresponding to a "weak" shock wave. For $\varphi = \varphi^*$ the solution is unique. The value of φ^* can be determined by solving Eq. (2.7) for φ while simultaneously satisfying the condition $\partial\theta_2/\partial V_2 = 0$ (see [10]). An analysis of the function $\theta_2(V_2)$ shows that this corresponds to the point of the maximum of θ_2. Thus, instead of Eq. (2.7), for each pair p_1, T we solve the equation

$$\theta_1(\varphi, p_1, T) - \max_{V_2} \theta_2(\varphi, p_1, T, V_2) = 0$$

or

$$\min_{V_2} [\theta_1(\varphi, p_1, T) - \theta_2(\varphi, p_1, T, V_2)] = 0.$$

The algorithm for determining φ^* for the case of porous metals and the accuracy attainable differ in no way from those described above. The accuracy in calculating p_2 and φ^* is actually determined only by the accuracy in assigning the initial data and the accuracy of interpolation from the tables. On the whole, one can guarantee that the accuracy in determining p_2 and φ^* in the entire investigated region of values of p_1 and T is no worse than 0.1%.

3. Discussion of Results

In the calculations the initial temperature of the aluminum was varied from 20 to 520°C, that of the copper from 20 to 720°C, and that of the tungsten from 20 to 1020°C. Here the variation of the initial specific volume of the medium reached several percent and the variation of the thermal energy reached several hundred percent. Such an increase in the thermal energy results in the fact that the shock-wave pressure required to compress the medium to a given density grows by several tens of percent owing to the additional increase in the thermal component.

The results of the calculations show that when the amplitude of the incident shock wave is several tens of gigapascals the change in the critical angle does not exceed 10%, which only slightly exceeds the limit of accuracy of the existing experimental methods of recording, according to [8-10]. Graphs of the change in the critical angle $\Delta\varphi^* = [1 - \varphi^*(T)/\varphi^*(20)]\cdot 100\%$ as a function of the temperature and of the amplitude of the incident wave are shown in Fig. 2.

A significant change in the critical angle is observed upon a decrease in the initial density of the medium (through an increase in porosity). In Table 2 we present the calculated values of the critical angle for different values of the initial density of the medium for an incident shock wave of amplitude p_1 = 10, 20, and 50 GPa and a temperature of 20°C. Dashes denote the absence of data on the equation of state of the medium for the high degrees of compression needed to calculate the parameters of the reflected shock wave. The pressure change behind the front of the reflected shock wave caused by preliminary heating of the medium depends both on the intensity of the incident wave and on the angle of incidence on the reflecting surface.

An analysis of the results obtained shows that in the investigated range of variation of the initial temperature and of the intensity of the incident wave the reflection pressure change lies mainly in the range of 10%. In Fig. 3 we show the influence of the angle of incidence on the relative reflection pressure change $\Delta p_2 = [1 - p_2(\varphi)/p_2(\varphi^*)]\cdot 100\%$ in copper at temperatures of 20 and 720°C and incident wave amplitudes of 20 and 50 GPa. Curves of the relative reflection pressure change $\Delta p_2 = [p_2(T)/p_2(20) - 1]\cdot 100\%$ as a function of temperature for a fixed angle of incidence $\varphi = \varphi^*$ are presented in Fig. 4.

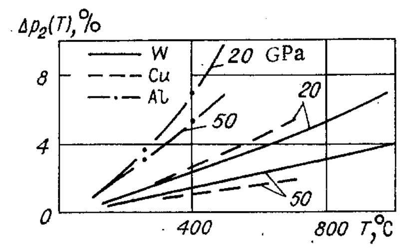

Fig. 4

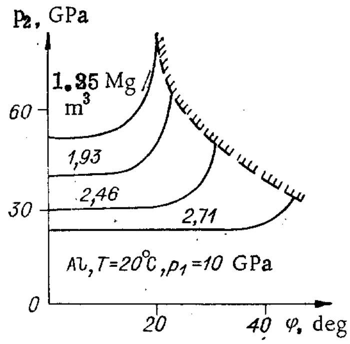

Fig. 5

TABLE 2

Medium	Initial density, Mg/m³	Amplitude of incident wave, GPa	Critical angle, deg	Medium	Initial density, Mg/m³	Amplitude of incident wave, GPa	Critical angle, deg
Tungsten	19,30	10	56,6	Aluminum	2,71	10	45,6
		20	54,6			20	39,9
		50	45,5			50	36,2
	14,50	10	17,9		2,46	10	31,0
		20	19,0			20	32,2
		50	—			50	—
Copper	8,90	10	49,9		1,93	10	22,0
		20	43,5			20	24,0
		50	36,5			50	—
	7,81	10	24,1		1,35	10	20,0
		20	26,8			20	22,5
		50	28,0			50	27,0
	7,35	10	20,3				
		20	23,9				
		50	26,1				

The influence of the initial density of the medium on the reflection pressure is shown in Fig. 5 on the example of the reflection of shock waves in aluminum. The amplitude of the incident wave is 10 GPa and the temperature is 20°C. The numbers near the curves denote the initial density of the medium. The hatched region is inaccessible to regular reflection. It is seen that the reflection pressure increases significantly with a decrease in the initial density. The relative reflection pressure change $\Delta p_2 = [p_2(\rho_{00})/p_2(\rho_0) - 1]\cdot 100\%$ (ρ_{00} and ρ_0 are the densities of the medium in the porous and monolithic states, respectively) can reach hundreds of percent. And this increase is the larger, the lower the intensity of the incident shock wave and the closer the angle of incidence to the critical value [10].

Thus, the results of this investigation show that the influence of the parameters of the initial state of the medium on the shock-wave loading can prove to be insignificant as well as very large.

Thus, a change of several hundred degrees in the initial temperature leads to pronounced changes in the Hugoniot adiabatic curve. At the same time, the changes in the reflection parameters are rather slight and lie mainly within the limits of the experimental errors of the existing recording methods.

A change in the initial density not connected with heating can lead to a considerable decrease in the size of the region of regular reflection regimes and to a severalfold increase in the reflection pressure. The latter fact allows one to use porous media to enhance the action of shock waves [17].

The influence of the initial density on the reflection parameters can be explained using the following qualitative arguments. The more compressible the medium is, the larger the angle θ_1 at which the stream is deflected in the incident shock wave. Since the transition from regular to irregular reflection sets in when the angle θ_1 becomes greater than the limiting value by which the reflected wave can turn the stream, in a more compressible (porous) medium the critical angle should be smaller than in a monolithic medium.

The main cause of a pronounced increase in the reflection pressure with a decrease in density consists in the following: The more compressible the medium is, the higher the mass velocity behind the shock-wave front for a given pressure amplitude, and hence the higher the stagnation pressure of the stream against the barrier.

Preliminary heating of the medium leads to two effects at once: a decrease in the initial density due to thermal expansion and an additional increase in the thermal component of the pressure by an amount proportional to the increase in internal energy, which opposes compression. The smallness of the changes introduced by heating is evidently due to the fact that the two effects have diametrically opposite actions on the compressibility of the medium, and hence on the reflection parameters. It is obvious that the result must depend on the relation between the heat capacity of the substance, characterizing the change in internal energy with a change in temperature, and the thermal expansion coefficient, which characterizes the change in density.

In this paper we did not consider the reflection of shock waves from deformable barriers. According to [18, 19], the reflection parameters depend on the compressibility of the barrier. Taking into account the above arguments about the influence of temperature on the compressibility of the medium, one must expect that this influence will be slight for metallic barriers.

LITERATURE CITED

1. P. C. Johnson, B. A. Stein, and R. S. Davis, "Temperature dependence of shock-induced phase transformations in iron," J. Appl. Phys., 33, No. 2 (1962).
2. N. L. Coleburn and J. W. Forbes, "Anomalous effect of temperature on shock-wave propagation in Cu–Zn," J. Appl. Phys., 40, No. 11 (1969).
3. G. A. Adadurov, V. I. Gol'danskii, et al., "Dynamic compression of solids at superlow initial temperatures," Izmer. Tekh., No. 9 (1981).
4. I. N. Gemnitskii, M. A. Vainberg, et al., "Production of piezoceramics by the method of explosive compression," Izmer. Tekh., No. 9 (1981).
5. É. O. Mindeli, Z. I. Mgeladze, et al., "Influence of preliminary heating on the explosive hardening of a solid alloy," Fiz. Goreniya Vzryva, No. 4 (1978).
6. E. O. Mindeli, É. Sh. Chagelishvili, et al., "Explosive compression of tungsten carbide powder at high initial temperatures," in: Second All-Union School Seminar on Explosion Physics and the Experimental Use of an Explosion [in Russian], Novosibirsk (1980).
7. É. O. Mindeli, G. P. Licheli, et al., "Influence of preliminary heating on the process of deposit of solid particles onto plane surfaces," Fiz. Goreniya Vzryva, No. 5 (1977).
8. L. V. Al'tshuler, L. B. Kormer, et al., "Irregular regimes of oblique collision of shock waves in solids," Zh. Eksp. Teor. Fiz., 41, No. 5 (1961).
9. N. A. Kostyukov and A. M. Staver, "Oblique collision of shock waves in porous metals," in: Proceedings of Third Symposium on the Explosive Treatment of Metals, Mariánské Lazne [in Russian], (1976).
10. N. A. Kostyukov, "Influence of the initial density of the substance on the regime of oblique collision of shock waves," Zh. Prikl. Mekh. Tekh. Fiz., No. 3 (1977).
11. T. V. Bazhenova and L. G. Gvozdeva, Nonsteady Interaction of Shock Waves [in Russian], Nauka, Moscow (1977).
12. A. C. Mitchel and M. van Thiel, "Effect of temperature on shock-wave propagation in Cu–Zn alloys," J. Appl. Phys., 45, No. 9 (1974).
13. F. A. Baum, L. P. Orlenko, et al., Physics of an Explosion [in Russian], Nauka, Moscow (1975).
14. W. Herrmann, "Constitutive equation for the dynamic comparison of ductile porous materials," J. Appl. Phys., 40, No. 6 (1969).
15. R. K. Linde, L. Seaman, and D. N. Schmidt, "Shock response of porous copper, iron, tungsten, and polyurethane," J. Appl. Phys., 43, No. 2 (1972).
16. A. A. Bakanova, I. P. Dudoladov, and Yu. N. Sutulov, "Impact compressibility of porous tungsten, copper, and aluminum in the low-pressure region," Zh. Prikl. Mekh. Tekh. Fiz., No. 2 (1974).
17. N. A. Kostyukov, "Criteria for the strengthening of an oblique shock wave using a layer of porous substance," Fiz. Goreniya Vzryva, No. 5 (1980).
18. N. M. Sternberg and D. Piacesi, "Interaction of oblique detonation waves with iron," Phys. Fluids, 9, No. 7 (1966).

19. N. A. Kostyukov, "Properties of the oblique reflection of shock waves from a barrier in powders," in: Din. Sploshnoi Sredy, No. 29 (1977).

PROPAGATION OF STRESS WAVES IN LAYERED MEDIA UNDER IMPACT LOADING (ACOUSTICAL APPROXIMATION)

N. Kh. Akhmadeev and R. Kh. Bolotnova

UDC 534.211:539.42:539.63

1. INTRODUCTION

The impact loading of various bodies and structures by the detonation of an attached high-explosive charge, the firing of a projectile (driver), or thermal irradiation with a pulse of duration $\sim 10^{-9}$ sec can result in scabbing of the loaded bodies near their free surfaces, which originates in the unloading phase under the action of a stress wave. The action of tensile stress can be abated and the danger of scabbing can be diminished by the application of special layered systems, in which the generated shock impulse is partitioned at the layer interfaces into a branched system of compression and tension waves. It is technologically feasible at the present time to construct layered systems and structures from various types of materials by, e.g., the explosive welding of metal layers not amenable to conventional welding techniques, vacuum evaporation or detonation flame spraying of condensed films, the bonding of a series of layers, etc. The problems of shock transmission in layered systems have been investigated in studies of the influence of the parameters of colliding plates and buffer layers on the scabbing process [1] and on the quality of a welded joint between bonded materials in explosive welding [2]. An analysis of the wave processes for two- and three-layer systems has been carried out in [3-5]. A detailed theoretical and experimental study of the attenuation of shock waves in layered materials is given in [6]. The propagation of acoustic and electromagnetic waves in layered media has also been investigated in application to geophysical problems [7].

The objective of the present study is to analyze the generation of stress waves in a planar layered medium under impact loading in the acoustical approximation and to explore the possibility of preventing scabbing.

2. MODEL OF AN ELASTIC LAYERED MEDIUM

Let a layered medium consist of n different layers. A schematic diagram of such a medium of length L in the one-dimensional planar case is shown in Fig. 1. Each i-th layer of the meidum (i = 1, 2,...,n) is characterized by the true density ρ_i^0, the dynamic rigidity $Z_i = \rho_i^0 a_i$ (a_i is the longitudinal sound velocity in the i-th layer), and the length l_i $(L = \Sigma_{i=1}^n l_i)$. The quantity Z_i is also called the acoustic impedance and is related as follows to the elastic modulus of the material $E_i (a_i = \sqrt{E_i/\rho_i^0})$: $Z_i = \sqrt{E_i \rho_i^0}$. We denote the boundary between the i-th and (i + 1)-st layer by K_i. We assume that the impact loads are not too strong, so that the problem can be restricted to the acoustical approximation, i.e., we assume that the rigidity of the layers Z_i does not depend on the intensity of the transmitted waves and, hence, that the conditions $\rho_i^0 = \rho_{i0}^0$, $a_i = a_{i0}$ hold everywhere; then $Z_i = Z_{i0}$ (ρ_{i0}^0, a_{i0} correspond to the standard initial conditions $p_0 = 0$, $T_0 = 300°K$). We assume that a rectangular compression pulse J_1^I of duration t^w is generated in the first layer as a result of impact action along the r axis. In the subsequent transmission of J_1^I through the layers, multiple reflections take place at the boundaries K_i owing to the differences in the rigidities Z_i of the layers; these reflections produce reflected pulses J_i^R and transmitted pulses J_{i+1}^T of the same duration t^w. The pulses J_i^R and J_{i+1}^T can be either compression or tension pulses, depending on the ratio between the rigidities Z_i and Z_{i+1}. If the tensile stresses in the i-th layer exceed a certain threshold value σ_i^* characterizing the strength properties of the material of the i-th layer in tension under dynamic loading, scabbing will be possible inside the layer either almost instantaneously [8] or with a certain delay [9]. We assume that the tensile strength in each intermediate layer K_i, denoted by $\sigma_{i,i+1}^*$, is large and at

Ufa. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 1, pp. 125-133, January-February, 1985. Original article submitted December 7, 1983.

 0021-8944/85/2601-0114$09.50