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Propagation of Laser Generated Shock Waves through Heterogeneous Metallic Mediums

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Abstract

This paper deals with an analytical study of shock waves propagating in heterogeneous metallic mediums. A shock wave travels through most media at a speed higher than ordinary wave. The propagation of a shock wave created by a laser impact over a metallic surface is considered here. In the process of Shock wave generation, a high-pressure surface level is reached using a nanosecond laser pulse that heats the surface of the material and generates adense plasma expansion. The pressure reaches few GPa so that shockwaves are generated and propagated in the bulk of the material. Whitham method, a powerful analytical method for shock waves, has been employed to obtain the analytical relations for shock velocity, shock strength and pressure behind the freely propagating shock. Numerical calculations have been performed for shock velocity, shock strength, pressure, adiabatic sound velocity, and compression behind the shock (δ) and their variation with propagation distance have been discussed. A sharp decrease in shock velocity and pressure behind the shock whereas a steadily increasing shock strength with propagation distance has been observed. Particle velocity, adiabatic sound velocity and compression parameter also show a gradual decrease as the shock advances in the medium. Effect of overtaking disturbances has been evaluated by considering Yadav's approach.

Key words : Weak shock, freely propagating shock, Witham approach, Shock strength.

1. Introduction

The laser generated shock waves result from the expansion of a high-pressure plasma caused by a nanosecond pulsed laser. Laser driven shock wave propagation in a transparent material such as plexiglass created upon a layer of gold is very important for industrial point of view. Takayama *et. al.* made an experimental study for the stability of converging cylindrical shock waves and concluded that the converging cylindrical shock wave is always unstable and sensitive to the structure of the cylindrical shock tube[1].

As per the study of Dobromyslov *et al.* the formation of adiabatic shear bands (ASBs) in different metals and alloys occurs at high strain rates and levels of stresses[2]. The method of loading by spherical converging shock waves is the most perspective method for the investigation of the formation and evolution of the ASBs and other instabilities of the plastic flow. The effect of impact loading on the structure of an austenitic steel was studied by Kozlov *et al*.[3].

The propagation of normal shock wave through a layer of incompressible porous material has been investigated by Torrens *et al*.[4]. A shock tube study was carried out to examine the interaction of a normal shock wave with a thin layer of porous, incompressible cellular ceramic foam. The numerical model was proposed to explain the behavior of the transmitted flow field.

Kanal *et al.* studied the response of metals and alloys to shock wave loading at elevated temperatures[5]. Shock wave tests was carried out for metal single crystals, polycrystalline metal of different purity, and for alloys. It was observed that in poly crystalline metals, melting starts earlier at grain boundaries, which is supposed to be a pre- melting phenomenon. As approaching the melting curve, anomalous growth of the dynamic yield stresss was observed for low strength alloys which decreases with temperature. Parallel molecular dynamics simulations of ejection from the metal copper and aluminium under shock loading has been investigated by Qi-Feng *et al*.[6]. Large scale non equilibrium molecular dynamics simulations are used to investigate the ejections of the metal under a shock loading. A model of non-linear longitudinal strain wave propagation in metal plates with quadratic non linearity of elastic continuum, exposed to laser impulses, is developed by Mirzade[7]. Electrical pulse formation during high temperature reaction between Ni and Al has been investigated by Setoodeh *et. al.*[8].

Bedoya Matinez *et al.* studied and presented calculations of the zero-pressure melting temperature of a series of face centered cubic (fcc) metals[9]. Melting temperatures were obtained by calculating the Gibbs free energy of the solid and liquid phases, and finding the temperature at which they match. Propagation of shock waves in rigid porous materials has been investigated by Levy *et al*.[10]. Huang *et al.* studied the shock wave formation and propagation in two dimensional granular materials under vertical vibration by digital high-speed photography by exploring the effect of driving parameters and particle number on the shock[11].

The study of motion of shock waves through certain metals was undertaken by Yadav *et al*.[12]. The propagation of shock waves in uniform real gas atmosphere for plane, cylindrical and spherical symmetries of the wave was also studied by the group of Yadav *et al*.[13]. Rana *et. al.* studied the plane hydro magnetic shock waves through the uniform and non-uniform media and observed some interesting and peculiar results[14]. G. Nath performed an experimental investigation of cylindrical shock waves generated by a moving piston in a rotational axis symmetric non-ideal gas with conductive and radiative heat fluxes in the presence of azimuthal magnetic field[15]. Theoretical studies concerning the presence or absence of magnetic field on the behaviour of cylindrical shock waves in rotating ideal gas employing Lie group transformation method were also undertaken by Nath G. and Sumeeta Singh[16]. They carried out these studies by assuming adiabatic flow conditions. Two kinds of solutions *i.e.,* power law and exponential law shock path were examined, however exact solutions were obtainable only in the latter case. Sumeeta Singh studied for the similarity solutions for magneto gas dynamic cylindrical shock waves in rotating non-ideal gas using Lie Group theoretic method[17]. Coupled models for the propagation of shock waves in cylindrical and spherical geometries were also investigated by the research group of C. Y. Cao[18]. The propagation of cylindrical shock waves in an adiabatic non-ideal gas was studied by Singh et al. using Lie group transformations (LGT)[19]. Gupta *et al*. studied the evaluation of acceleration waves in non-ideal radiative magnetogasdynamics[20]. R. Chandra and S. Singh made an analytical study on the effect of overtaking disturbances in the propagation of spherical shock waves through solids, especially metals such as Aluminium and Copper and flow variables were calculated analytically as well as estimated numerically. Expressions for the pressure and the particle velocity behind the shock wave were also obtained and discussed for various parameters.

In this paper the free propagation of cylindrical and spherical strong converging shock waves in Aluminium metal is being investigated. Chisnell- Chester method has been used to obtain the analytical expressions for shock velocity and shock strength. A very significant and important phenomenon, the effect of overtaking disturbances is neglected to make the problem easier and analytical relations for flow variables are obtained numerically. Their dependences on various parameters are discussed with the help of graph and tables.

The shock velocity, shock strength, pressure and particle velocity behind the shock is computed using equations (5) to (7). The variation of pressure with parameter δ and propagation distance is obtained for both cylindrical and spherical shock waves. It is found that shock velocity decreases with propagation distance and shock strength increases as shock progresses in Al metal.

Finally, the results accomplished here have also been compared with[22].

2. ***Basic Equations***

The equations of conservation of mass, momentum and energy are given by –

$$\frac{\partial \rho}{\partial t} + u\frac{\partial \rho}{\partial r} + \rho\frac{\partial u}{\partial r} + \frac{\alpha \rho u}{r} = 0 \tag{1}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial r} + \frac{1}{\rho}\frac{\partial p}{\partial r} = 0 \tag{2}$$

$$\frac{\partial p}{\partial t} + u\frac{\partial p}{\partial r} + c^2\left(\frac{\partial \rho}{\partial t} + u\frac{\partial \rho}{\partial r}\right) = 0 \tag{3}$$

where, r indicates the position of shock front at time t and p, ρ, c and u represent the pressure, density, sound velocity and particle velocity respectively. For cylindrical symmetry α=1 and α=2 for spherical shock waves. The shock velocity U and particle vselocity u in the metal have been assumed to be connected by a linear combination

$$U = a + bu \tag{4}$$

where, a and b are constants of the metal.

3 *Boundary Conditions*

If subscript '2' and '1' denote the quantities behind and ahead of the shock front, then mechanical jump conditions across the shock front are given by the expressions

$$p_2 = \frac{\rho_1 a^2 \delta(\delta - 1)}{\{b - \delta\}(b-1)^2} \tag{5}$$

$$U = \frac{a\delta}{\{b - \delta(b-1)\}} \tag{6}$$

$$u_2 = \frac{a(\delta - 1)}{\{b - \delta(b-1)\}} \tag{7}$$

Where, δ represent the compression behind the shock front.

4. *Mathematical Description*

The characteristic form of basic equation (1)-(3) for freely diverging shock is

$$dp + \rho c du + \frac{\alpha \rho c^2 u}{u + c}\frac{dr}{r} = 0 \tag{8}$$

using boundary conditions (5), (6) and (7) in equation (8) and after simplification, we get

$$\alpha \log\frac{r}{r_0} = -\delta - \Gamma\left(\frac{\delta^2}{2} - \delta\right) + \frac{\Gamma}{2b}\delta^2 + b\log\delta + \frac{b\Gamma}{2}(\delta - \log\delta) + \frac{b^2\Gamma}{4}\left(\delta - 3\log\delta - \frac{3}{\delta} + \frac{1}{2\delta^2}\right) + \frac{b^2}{2}\left(\log\delta + \frac{1}{\delta}\right) + \frac{b^3}{2}\left\{\log\delta - \frac{1}{2\delta^2} + \frac{2}{\delta}\right\} + \frac{b^2\Gamma}{\delta} + b^2\Gamma\log\delta + \frac{1}{(b-1)}\log\{b - \delta(b-1)\} \tag{9}$$

The equation(9) represents the relation between parameters delta (δ), propagation distance(r/r_0), gama (Γ) for cylindrical shock waves.

5. Results and Discussion

The relation (9) is used to compute δ for different values of r/r_0 for Al metal perturbed by cylindrical shock waves. Taking a=5.328, b=1.338, ρ=2.785 for Al metal, δ is computed for cylindrical shock (α=1). Using this value of δ the variation of flow variables are obtained and discussed. The flow variables for cylindrical shock wave are given in table 1 for Al metal.

Table 1 : The variation of shock velocity, shock strength, pressure, Particle velocity, Adiabatic sound velocity and δ with propagation distance (r/r_0) for freely propagating cylindrical conversing shock waves in Al metal. (a=5.328, b=1.338 , ρ= 2.785).

Propagation Distance	**Shock Velocity**	**Shock Strength**	**Pressure**	**Particle Velocity**	**Adiabatic Sound Velocity**	**Delta**
r/r_0	U	U/c	P	U	C	δ
1.0	159.9687	0.5033	51487.370	115.5687	317.8101	3.6029
1.2	100.3539	0.6621	15962.635	70.5885	151.5697	3.3715
1.4	69.4564	0.6823	9231.4073	47.8231	101.7988	3.2260
1.6	34.9496	0.8157	2155.1787	22.1419	42.8435	2.7288
1.8	24.6445	0.8377	990.3710	14.4376	28.4015	2.4145
2.0	19.4618	0.8927	572.7496	10.5670	21.8009	2.1880
2.2	16.1071	0.9084	480.8461	8.0528	17.7315	2.0013
2.4	13.6521	0.9193	236.4328	6.2212	14.8502	1.8372
2.6	11.7042	0.9267	155.3788	4.7667	12.6298	1.6871
2.8	10.0731	0.9489	100.6745	2.5637	10.6155	1.5458
3.0	8.5642	0.9954	85.2541	2.3654	9.5423	1.3325

5.1 *Variation of shock velocity with propagation distance*

The variation of shock velocity with propagation distance (r/r_0) is displayed in figure 1. Shock velocity decreases from 159.9687 to 8.5642 (for Al) as cylindrical shock moves from propagation distance 1.0 to 3.0 [table 1 and figure 1].

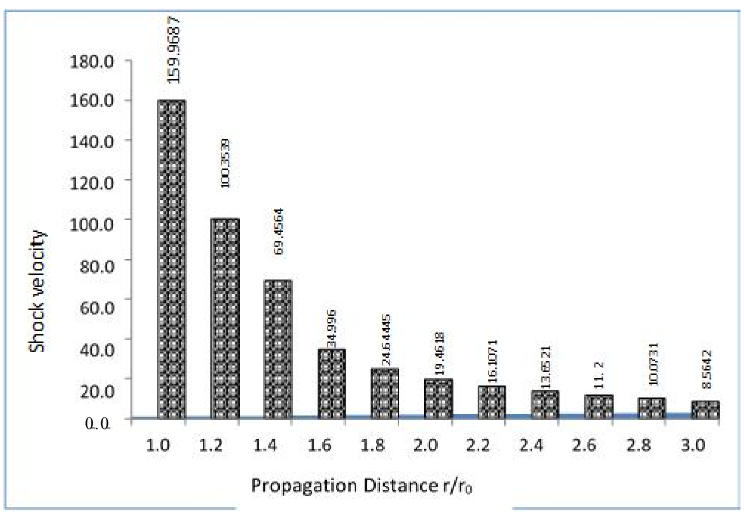

Fig. 1 : Variation of shock velocity with propagation distance for cylindrical shock propagating freely in Aluminium metal.

5.2 ***Variation of shock strength with propagation distance***

Shock strength increases from 0.1975 to 0.7563 for Al metal, as cylindrical shock moves from distance 1.0 to 3.0 [table 1 and figure 2].

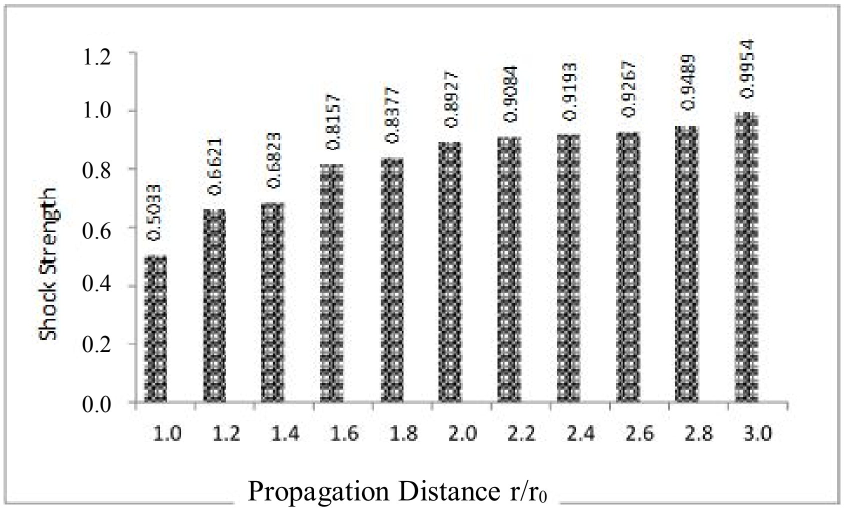

Fig. 2 : Variation of shock Strength with propagation distance (r/r_0) for Al metal.

5.3 ***Variation of pressure with propagation distance***

The pressure behind the shock is computed using equations (14) and (5). The variation of pressure for cylindrical shock waves with parameter d are shown in table 1 and figure 3 with propagation distance decreases from 51487.3700 to 85.2541 for Al metal, as cylindrical shock moves from distance 1.0 to 3.0 [table1 and figure 3].

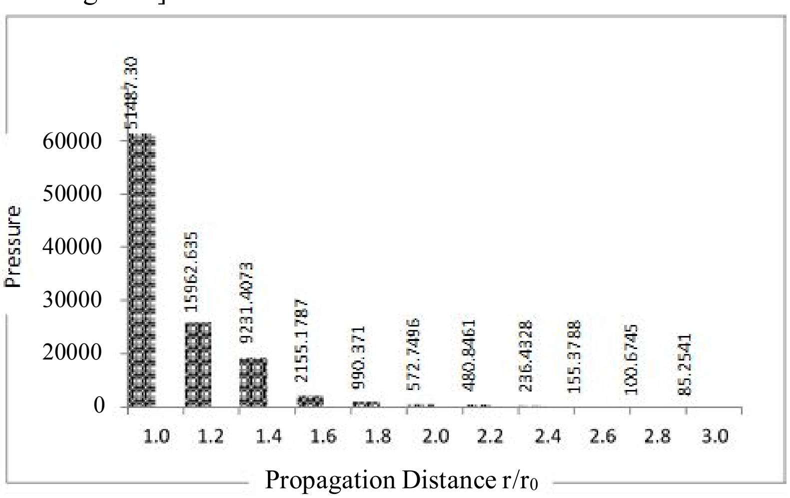

Fig. 3 : Variation of pressure with propagation distance for cylindrical shock in Al metal.

5.4 *Variation of particle velocity with propagation distance*

Particle velocity behind the shock is computed using equation (9) & (7). The variation of particle velocity for cylindrical shock waves with parameter δ are shown in (table 1 and figure 4) with propagation distance (r/r_0).

Particle velocity decreases from 115.5687 to 2.3654 for Al metal as cylindrical shock wave moves from distance 1.0 to 3.0 (table 1 and figure 4).

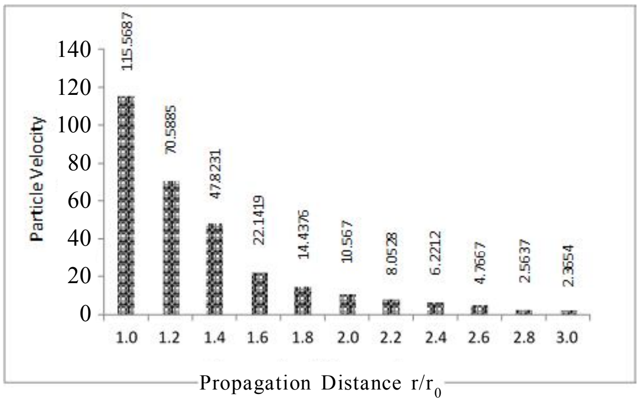

Fig. 4 : Variation of particle velocity with propagation distance (r/r_0) for cylindrical shock propagating freely in Aluminium.

5.5 *Variation of adiabatic velocity with propagation distance*

Adiabatic sound velocity behind the shock is computed using equation (8). The variation of Adiabatic sound velocity for cylindrical shock waves with parameter δ are shown in (table 1 and figure 4) with propagation distance.

Adiabatic sound velocity decreases from 317.8101 to 9.5423 for Al metal, as cylindrical shock wave moves from distance 1.0 to 3.0 (table 1 and figure 5).

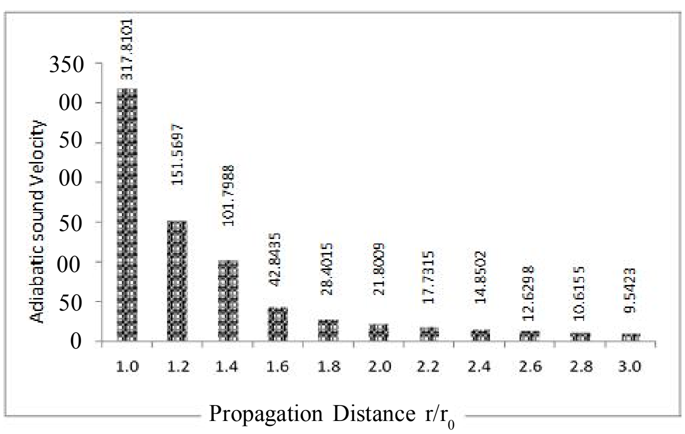

Fig. 5 : Variation of Adiabatic sound velocity with propagation distance for cylindrical shock in Al metal.

5.6 *Variation of δ with r/r_0*

Delta (δ) decreases from 3.6029 to 1.3325 for Al metal as cylindrical shock wave moves from distance 1.0 to 3.0 (table 1 and figure 6).

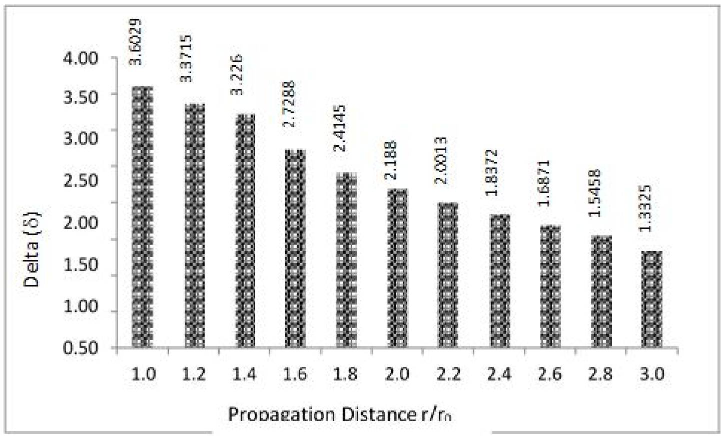

Fig. 6 : Variation of Delta (δ) with propagation distance (r/r_0) for cylindrical shock in Al metal.

6. Conclusions

It is concluded from above computations that the shock velocity (U), pressure (p) and the particle velocity (u) decrease with propagation distance (r/r_0) as the spherical shock waves propagate along the metals. However, the shock strength (U/c) increases with the advancement of shock wave in the metal under consideration. The adiabatic sound velocity and the compression behind the shock (δ) also show a gradual decrease with increasing propagation distance.

These results obtained here may be useful for applications in many different fields of engineering including but not limited to astronomy, Geo physics, hypersonic flight exportations, plasma physics, aviation mechanical engineering and medicine to name just a few of them. The study might prove to be of great significance in the medical field for the treatment of various human diseases.

Scope of Future Work

The present study may be extended to shock wave propagation through certain other metals keeping in view their industrial and medical applications. Herein we have relied on numerical and analytical calculations using some basic numerical tools. So future studies can be experimental as well as theoretical using other advanced numerical calculation software and a critical comparison of theory with experiments can be undertaken.

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