Some Phenomenological and Metallurgical Aspects associated with Impact of High Speed Projectiles

Adnan I. O. Zaid, Hashem S. Alkhaldi, Shahnaz M. Alkhalil

Abstract— The impact of high speed projectiles involves velocities lies between few hundreds to few thousands m/s; and should be less than the sonic speed of either the projectile or target materials. It depends on many parameters: projectile and target materials, impact velocity, incident angle and the mass and shape of the projectile impacting end. In this paper, some of the phenomenological aspects associated with the impact of high speed projectiles are presented and discussed which include impact velocity, its length, shape of its impacting end, mode of deformation. Furthermore, the damages caused by it are also given and discussed together with methods of protection.

Index Terms— Impact, High speed projectiles, Velocity, Phenomenological aspects, Mode of deformation, Damages caused by it.

1 Introduction

PROJECTILE impact into metallic and non-metallic targets has engaged the military engineers for a long time aiming to develop faster projectiles and stronger armor. Unfortunately, military interest has meant that most of the work on the subject has been classified and not available to the public.
Current interest in the subject is mainly due to the need for information concerning:
(i). The dynamic properties of materials under high strain rate conditions as strain rates of the order 10^3/s are obtained during the projectile impact process, [1,2].
(ii). Simulation of the meteoroid hazard for space vehicles, [3]. and the containment of high speed fragments of the rotating parts of high speed turbines, [4].
(iii). The development in high energy rate manufacturing processes, e.g. explosive forming, electro-magnetic forming, explosive welding… ..etc.
The fundamental problem of projectile impact has not changed appreciably since the invention of canon and shot. It is mainly concerned with the determination of the projectile energy and the target resistance. Thus, the projectile penetration phenomenon became associated with the search for the appropriate relationship between the resisting force and the depth of penetration in the target. The first relationship seems to be that of the British Ballistician, Robins, in 1742, who proposed for a projectile- target combination that the resisting force is constant throughout the entire penetration process, [5]. Three years later Euler elaborated on Robins work and gave some experimental values for the assumed constant resisting force for Elmwood and earth, [6]. Despite the fact that he was capable of establishing some correct results, the Euler-Robin relationship is too crude to be of much practical use because it neglects the instantaneous conditions of the penetration process; even though this relationship remained essentially unchanged until 1829 when Poncelet published his theory which combined Euler's-Robins constant term which he referred to it as the breaking of the bonds which are responsible for the cohesion of solid or semi-solid material and the second term proportional to the square of the projectile impact velocity which is function of its kinetic energy. Although capable of explaining some penetration aspects it requires the determination of at least two numerical coefficients which are obtainable only by extensive firing tests. Moreover, each particular projectile-target configuration requires individual experimentation, as do the various parameters: impact velocity, angle of obliquity, etc., [7,8]. Along these lines, a considerable amount of experimental work was performed. The collected data was pertained to a wide variety of non-metallic materials, including clay, limestone, sand, brick and various kinds of wood. Some of this published work was summarized by Bashforth in 1873, [9]. For this reason, information of this type is of little use in problems involving armor penetration. The first information concerning the resistance of armor plate to penetration by high speed projectiles seems to be that which is reported in Encyclopedia Britannica in 1937, where the following formula was given in the form of:

$$W = 1/2\, M\, V^2 = C\, T^n\, R^{3-n}$$

Its velocity, R its radius T is the thickness of the armor plate and C and n are constants. Where 2 > n > 4/3 nd C depends on the strength of the steel used in the armor. Since then, many theoretical models using different concepts were developed. Bethe developed a model in which the progressive expansion of the hole in the plate was considered,[10]. Using his model , he was able to determine the total work required to expand the hole to radius R, as:

$$W = 2\, \pi\, R^2\, T\, Y$$

Where Y is the stress difference between the hoop stress, (σ_θ) and the radial stress, (σ_r) and assuming the stress perpendicu lar to the plate equals zero. Later, this model was modified by

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Taylor by relating the principal stress difference ratio to the principal strain difference ratio and obtained,

$$W = 1.33\, \pi\, R^2\, T\, Y$$

Later, Taylor recognized that inertia effects could not be ignored and introduced a parameter, $V = \rho U^2 / Y$, where ρ and Y are the density and the yield stress of the target material and U is the radial velocity at the edge of the hole, [11]. The measurement of the forces in armor penetration was reported in Refs. [12,13]. Thomson, [14] made a quasi-dynamic model of the penetration process considering the projectile energy to be dissipated in plastic deformation of the plate and obtained expressions relating the energy, E, to the projectile length, L, its radius, R, velocity, V, density, ρ, and the target thickness, ho, and yield stress, Y, for conical and ogival projectile respectively as:

$$E = \pi R^2 ho \{ Y/2 + \rho (V R / L)^2 \},$$

$$E = \pi R^2 ho \{ Y/2 + \pi^2 X\, 3 \rho/16 \; (V R / L)^2 \}$$

The last equation was later modified by Sodha and Jain, [15], to:

$$E = \pi R^2 ho \{ Y/2 + \pi^2 X \rho/16 \, (V R / L)^2 \}$$

Using the kinetic energy of the projectile, Brown developed a model for determining the minimum plate thickness necessary to contain a high-speed projectile, [16]. It is worth mentioning that in the above energy balance models, no allowance was made for the effects of wave propagation, crack formation, friction, strain rate and adiabatic heating.

Zaid and Paul used the principle of conservation of momentum, the instantaneous velocity of the projectile was described in terms of a quantity referred to it as the "effective mass" of the target plate enabled them to determine the acceleration, penetration and the resisting force for conical and ogival projectile, [17,18], and later extended to include truncated cones at oblique impact angles, [19].

Employing wave mechanics, Recht and Ipson obtained a complex expression for the minimum projectile velocity for perforation of certain plate thickness which involved: projectile length, diameter, density and sonic speed in addition to the plate density, shear strength, thickness and sonic speed, [20].

An approach based on viscoplastic theory considering the target plate to behave as a viscoplastic solid was used in Refs. [21-23]. The deformation and perforation of spherical and conical projectiles using high speed camera has been examined by Goldsmith et al, [24]. Furthermore, the containment of high speed flat ended cylindrical projectiles was investigated by zaid et al, [25-27].

After perforating target plate, the projectile may still possess a residual velocity; the determination of this velocity has been of interest to space and military engineers as it provides a means of comparing the effectiveness of different targets when subjected to the same impact conditions. This information is also used in considerations of the fuzing, safety and arming of shells, [28]. The residual velocity of steel projectile after perforating steel targets were determined experimentally and the results are reported in Refs. [28 ,29]. Nishiwaki developed a theoretical model for evaluation of the velocity drop which a bullet suffers upon perforating an aluminum target, [30]. He utilized the method suggested by Sutterlin for calculating the frictional resistance against projectile in the gun bore, [31].

2 Phenomenological Aspects of Projectile Perforation

Different situations may exist which depend on the physical and mechanical properties of both the projectile and target materials, (mainly the hardness) and impact velocity. If the target is rigid and its hardness is higher than the projectile hardness the impacting end of the projectile gets either deformed to mushroom shape at the impacting end along its length or fractured depending on its shape and impact velocity.

If the projectile is rigid and its hardness is higher than the target plate one of the following situations might take place depending on the impact velocity:

i). Penetration: a process of partial penetration of the projectile the thickness of the target plate, Fig 1(a).

ii). containment is the situation in which the impacting projectile penetrates the whole thickness of the target and is contained by it i.e. does not pass completely through it, Fig. 1(a), (b) and (c).

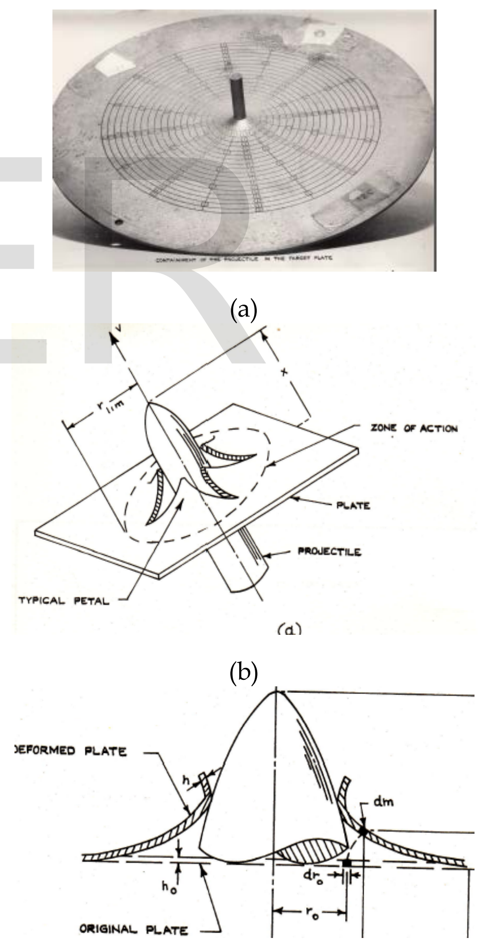

Fig. 1. (a) Containment of the projectile By the target plate; (b) containment of an ogival projectile, (petalling); (c) containment of a conical projectile, (bulging and folding)

iii). Perforation is the situation in which the projectile perforates the whole thickness of the target plate and drops with

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zero or with certain residual velocity as illustrated by Fig.1(c). Recently, the water backed has attracted many researchers under a new title.

3 Mode of Deformation

Following impact of the projectile with the center of the target plate, the latter is displaced axially, whilst simultaneously a plastic tensile wave moves out radially into the surrounding stationary material of the target plate which is supported around its periphery resulting in bulging it to a lesser degree. The amount of plastic deformation, bulging, (represented by the central deflection and the maximum affected radius) increases with increase of the projectile impact velocity up until the target plate becomes sufficiently stiff for a plug to shear off hence containment condition is achieved. This observation was noted by the author during investigation of the effect of target thickness for shielding against high speed fragments. The only significant difference is in the diameter of hole produced, being slightly larger at higher impact velocities. This is attributed to the radial velocity imparted to the target material at the edge of the hole, which acts to outweigh the reduction in diameter caused by the elastic recovery. Based on the results of this work and others published work of similar impact situations it can be concluded that the mode of deformation simply consists of bulging the target plate and shearing either a plug-in case of a flat ended cylindrical projectile, petalling in the impact center in case of an ogival ended projectile, or bulging and folding in the case of conical ended projectile. Figs 1(a), (b), and (c) respectively. Hence, the kinetic energy of the projectile is consumed in bulging and shearing of the target plate.

4 Damages caused by High Speed Impact

The damages will be discussed are those related to the impacting projectile and the target.

(A) Damages related to the Projectile:

Damages caused to projectile: depends on its nose, shape and velocity. It also depends on the strength and hardness of the target plate. Sseveral damages might take place in the projectile:

i) Mushrooming: if the target plate is single, rigid, harder and stronger than the projectile is softer than the target, the projectile will deform plastically at its impacting end and along its length causing mushrooming shape at the impacting end. The cause of it and the theoretical aspects related to it are discussed in detail in, Ref. [32].

ii) Fracture of the projectile. This might occur either during its free flight before reaching the target plate or during penetration or after passing through the target. These three types of fracture are caused by elastic stress waves either during transmission, reflection or interaction. It is worth mentioning that fracture may be single, (as the case of flat ended cylindrical projectile during its penetration of a laminated target plate of less hardness than the projectile as indicated in, Fig. 2 , or multiple fracture or complete destruction, these last two cases normally occur with conical projectiles made of brittle material and high stress levels.

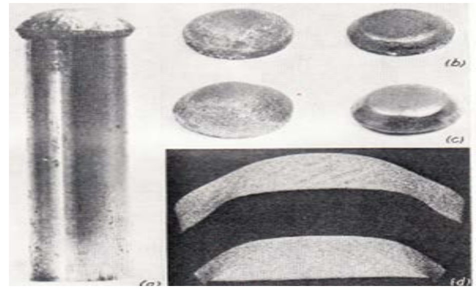


Fig. 2 A flat ended cylindrical projectile capped with the plug from the first plate.

(B). Phenomenological aspects and damages caused to the target:

The target might suffer some phenomenological, metallurgical and damages depending on its physical and mechanical properties and the developed pressure from the impact process e.g. tearing, twinning, phase transformation and scabbing from its free end in case of high pressure and thick plates. These are shown in Fig.3 (i), (ii), (iii) and (iv). Detailed discussion of the metallurgical aspects of these processes is given in Ref. [33].

(i). Tearing at the edge of the perforated target plate. This is shown in Fig.3 (i).

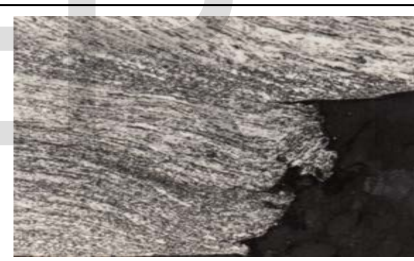


Fig.3 (i). Shows tearing at the edge of the perforated plate.

(ii) Twinning within the equi-axed structure of the mild steel target material. This occurs in the target plate if the projectile impact velocity is less than 130 m/s which causes pressure less than 100 KBar on the plate surface, Fig.3 (ii)

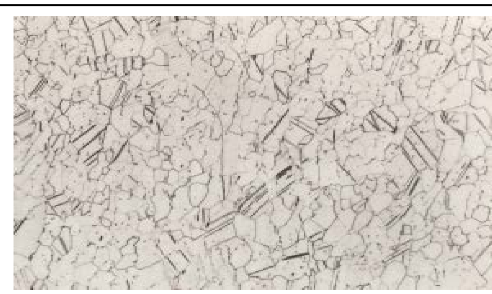
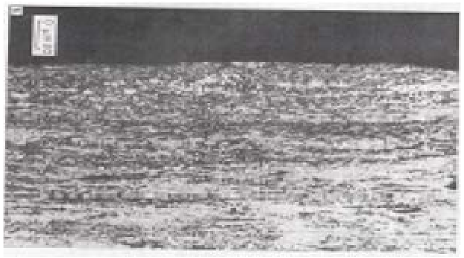
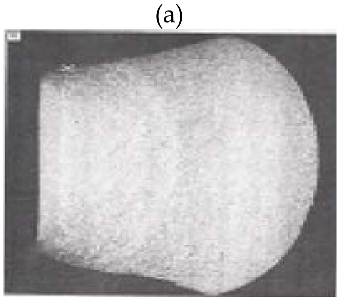


Fig.3 (ii) shows twinning within the main matrix of an equi-axe structure of a mild steel plate.

(iii). Recrystallization at the edges of the perforated hole and the recovered plug: this occurs normally in thick plates due to adiabatic heating, Fig.3 (iii).



(a)



(b)

Fig.3 (iii) Photomicrograph showing (a) partial recrystallisation (b) at the plug edge.

(iv). Phase transformation as indicated in Fig.3 (iv). The amount of transformation increases as the impact velocity increases which results in increase of pressure. It is worth mentioning that scabbing was not observed even with the thick plates, which indicates that the impact velocity and hence the pressure associated with it is lower than that required to cause scabbing.

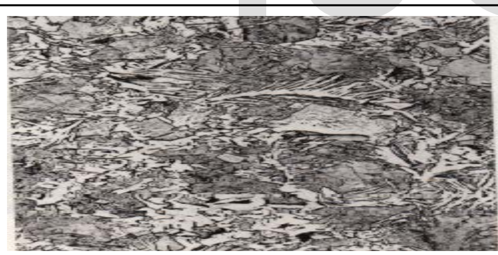


Fig.3 (iv) Photomicrograph showing the phase transformation in the target plate.

(v). Fracture of the recovered plugs. This occurred during studying the effect of the target hardness on the required energy for containment of flat ended cylindrical projectile. as shown in Fig. 4.

Fig. 4. Effect of target hardness on the recovered plugs.

5 Suggested Methods for Protection Against Projectile Impact

The following methods are suggested for protection:

i). Single, laminated with and without standoff distance backed and un-backed.

ii). Single plate shield backed with water.

iii) Utilization of severe plastic deformation methods using the equal channel angular pressing, ECAP, process

iv) Utilization of superplastic materials instead of the conventional materials in i), ii) and iii).

Review of the available literature reveals that most of the reported work is directed towards the use of structural members made of ordinary engineering materials and tested under quasi-static loading conditions whereas it is well known that projectile impact falls in the high strain rate category, 10^3 /s The behavior of the materials under quasi-static loading condition is quite different from its behavior under high rate loading i.e. dynamic particularly regarding their ductility and strain to fracture. Therefore, it is anticipated by the authors that a material which possesses high ductility at high rate of strain will be advantageous. Such materials are the superplastic materials: which are sensitive to strain rate and possess extra ordinary high ductility. Hence superplastic tin-lead alloy is suggested as an alternative to replace the ordinary engineering materials which is in addition to being superplastic at room temperature, it has the advantage of being rate sensitive at very low strain rates ranging from 1×10-2 to 1/s which is available in most testing laboratories in addition of being superplastic at the eutectic point which is at low temperature compared to other superplastic materials. Furthermore, it has the advantage of being usable after melting when gets damaged. This superplastic material was used successfully in protection of car occupants and saving the car from damage in car collision where different systems were designed and tested by the first author, [34].

The detailed designs and discussions of these systems are the subject of another paper.

6 Conclusion

(1). The literature on the subject is critically reviewed.

(2). Despite the voluminous literature on the subject, it is far from being complete and further research work is required especially on the protection methods against the damage.

(3). Different new systems for protection against the damages which are caused by projectile impact including utilization of superplastic materials are outlined in the paper which are applicable for protection in car collision and other similar high strain rate situations.

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