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Ballistic Impact Behaviour of a Tempered Bainitic Steel Against 7.62 mm Armour Piercing Projectile

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ABSTRACT

In this study, occurence of failure after the interaction between an armour piercing 7.62 mm caliber projectile and a tempered bainitic steel has been investigated. The shot was performed at zero degree with a projectile velocity of 840 m/s. After the shot, microstructural and fractographical examinations were carried out on the sample taken from the perforated region. In the etched sample, it was observed that the morphology of the original microstructure had changed and adiabatic shear bands (ASBs) were formed in regions close to the direction of penetration. Main failure is ductile (plastic) deformation was followed by cleavage after shot. Cracks due to adiabatic shear band and formation of abrasive wear were seen. The perforation mode of the steel was a typical petalling.

Keywords: Armour steels, microstructure, ballistic, perforation mode, impact behaviour, armour piercing projectile, tempered bainitic steel

1. INTRODUCTION

Modern firearms cause high level threat for both military and civilian targets. Contemporary protective materials play an important role in providing a barrier to such kinds of threats. Thus, studies on the search and development of protective materials such as steels[1,2], ceramics, and composite materials[3,4] have gained importance. Selecting appropriate material, processing conditions, and final microstructural and mechanical properties immensely affect the protective characteristics of materials under any dynamic loading. The importance of these effects for an armour steel has been currently studied by Karagoz[5], *et al*. They reported that alloying, solidification modelling in equilibrium condition, rolling and heat treatment conditions, microstructural factors such as matrix, inclusion, segregation, etc. and mechanical properties are very important for a quenched and tempered steel used as an armour material[5].

The necessary requirement for a protective material is to keep the damage factor of a projectile or a particle, having high kinetic energy and a certain geometry, at a minimum level to personnel and ammunition[6]. The hardness of the armour material will play a barrier role in the interaction with a projectile at high strike velocity[7]. A number of studies have revealed that the hardness has a direct effect on the ballistic performance of the materials[8-10]. An increase in the hardness of a material indicates that its ballistic performance will improve[11].

Armour steels are very popular as protective materials due to their usability and effective ballistic protection[11]. A type of armour steel, known as rolled homogeneous armour (RHA), has martensitic/bainitic or tempered martensitic/bainitic matrix and is used in several military vehicles such as tanks, howitzers, and other armoured combat vehicles[12]. On the other hand, steel is an indispensable material for many civilian applications, where high security is needed, like money chests, defence walls for banks, private armoured vehicles, etc. Armour steels due to their high strength, hardness and toughness properties[13] have a high level of energy absorbtion capability under any interaction with a projectile or a particle having high velocity.

The breakdown of the geometry of the projectile tip due to the hardness of the matrix of the protective material during penetration and the absorption of the kinetic energy to fail as cleavage rupture at first and then ductile rupture by plastic deformation, provide advantage for the usage of armour steels[14]. Considering these, it is clear that the microstructure of the steel is very important. Jena, *et al.* reported the role of microstructure on performance of a high-strength armour steel. In their study, the experimental results present the variation in the microstructure, hardness, and retained austenite of the two target plates as a function of heat treatment condition. The study concluded that the failure was caused by the decrease in resistance of the plate, possibly due to higher retained austenite and coarser martensitic structure[15]. As seen, every step such as alloying, casting and heat treatment, which contributes to the microstructure for the development of the ballistic performance, displays the main topics that must be investigated.

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Failure after interaction between 7.62 caliber projectile velocity of 840 m/s and a tempered bainitic steel has been studied. Bainitic steels offer high-strength and high toughness and have good potential as wear-resistant materials[16]. Many tests including erosion, abrasion, sliding and rolling-sliding conditions have been attempted on bainitic steels to understand their wear characteristics[17-20]. Especially in rail applications, bainitic steels stand in competition with pearlitic steels, however, the hardness of steel is an important factor for wear resistance under any loading that leads to wear[21]. Hence, bainitic steels under friction conditions are very attractive materials to investigate because of their high hardness compared to pearlitic steels. Clayton, *et al.* studied on wear behaviour of bainitic steels with different microstructures and found a certain relationship between wear rate and hardness of steel. As the wear rate decreases, the hardness of steel increases[22]. An intensive wear occurs due to penetration of a projectile to the target material. In this case, wear characteristic of the target material will affect the final failure, because a harder matrix increases the wear resistance of the material in addition to blunting of projectile tip. On the other hand, toughness is required for energy absorption of projectile under loading. Considering these approaches, a tempered bainitic steel having adequate hardness and toughness can be a good candidate as a protective material under dynamic loading.

2. EXPERIMENTAL STUDY

2.1 Materials and Methods

The chemical composition of the steel used in the study is shown in Table 1. Steel has been cast in Anadolu Steel Casting Co. at Kocaeli, Turkey. After casting, homogenisation annealing was performed on the slab at 1230 °C and then it was rolled at 1200 °C through 11 passes to get a plate having 12.7 mm thickness. The plate was deformed according to the specifications of ERDEMIR Co. at Zonguldak, Turkey. A 300 x 1000 mm steel plate was prepared for the ballistic test performed at Otokar Co. at Adapazari, Turkey.

Table 2 shows the heat treatment conditions applied on the experimental steel. As it may be seen, the heat treatment consists of austenisation, quenching, and finally tempering in accordance with the standards and with conventional armour steels[23-26]. All mechanical properties are represented in Table 3.

A shot was performed by a 7.62 mm caliber armour piercing projectile with a velocity of 840 m/s from 30 m. Table 4 shows the shot condition used for the experimental steel. Samples of the experimental steel collected before and after the shot (from the perforated zone) were prepared by metallographical methods. All samples were prepared by grinding with 320, 600, and 1000 mesh size SiC abrasives, respectively and then ground surfaces were polished with 3 μm diamond solution. Etching was carried out with nitale (3 per cent HNO_3) to characterise the microstructure. Light and scanning electron microscopes were used for both metallographical and fractographical examinations.

Table 1. The chemical composition (Wt-%) of the experimental steel

C	*Mn*	*Si*	*Ni*	*Co*	*Cr*	*Mo*	*Nb*	*V*	*Ti*	*B*	*P*	*S*	*Fe*
0.23	0.19	0.19	0.04	2.35	1.4	0.5	0.08	0.08	0.01	0.01	0.01	0.01	Balance

3. RESULTS AND DISCUSSIONS

3.1 Microstructural Characterisation

The microstructure of low carbon and alloyed steels consists of martensitic/bainitic matrix after application of austenisation and then quenching. Such a steel has high strength and hardness but not adequate toughness. Another heat treatment, known as tempering, is required to develop the toughness of the matrix. After tempering, the matrix exhibits a microstructure consisting of tempered martensite/bainite[27]. Tempered bainitic matrix contains lath type ferrite and intensive precipitates within ferrite phase and at the boundaries of the laths. The precipitates are mainly iron-based carbides known as cementite. On the other hand, it is possible to form alloy-based carbides as M_xC_y (such as MC, M_2C, M_7C_3, $M_{23}C_6$ etc.) type secondary carbides in the matrix depending on the chemical composition of the steel and these tempering temperature. These secondary carbides are harder than cementite and these increase the hardness of the matrix through secondary hardness effect. The dispersion of nanosized alloy carbides having coherent or semi-coherent interfaces with the matrix results in increase[28] in the hardness.

Figure 1(a) shows the light microscope image of the etched experimental steel. The matrix typically exhibits a tempered bainite microstructure. The regions in gray contrast

Table 2. The heat treatment conditions of the experimental steel

Austenisation	Quenching	Tempering
1000 °C, 45 min.	Water-quenching	600 °C, 45 min.

Table 3. The mechanical properties of the experimental steel

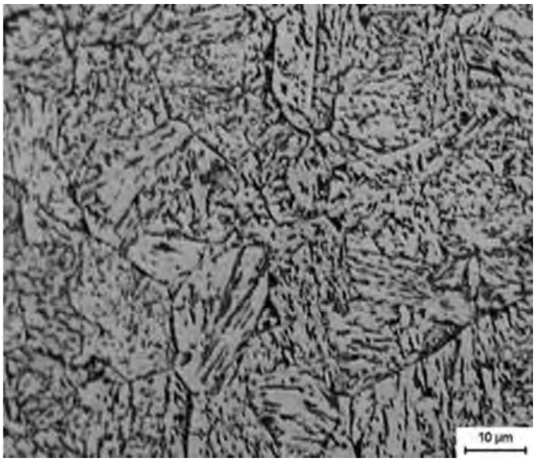
Tensile strength (MPa)	Hardness (HRC)	Elongation (%)	Impact toughness* (J)
1270	36	9.80	8.20

* Test type : Notched impact test, Test temperature: - 40 °C

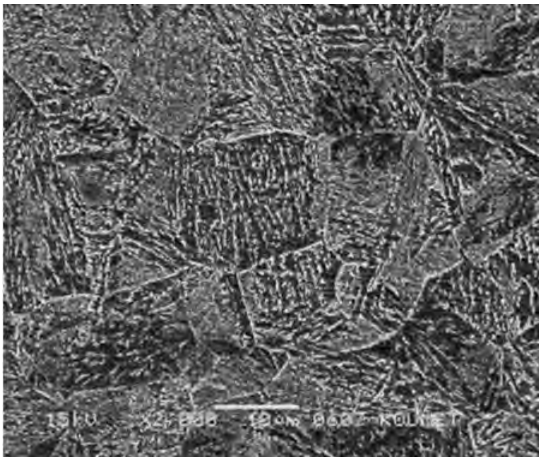
Table 4. The shot condition for the experimental steel

Distance	30 m
Shot angle	0°
Projectile type	API 55, 7.62-51 armour piercing
Ambient temperature	18.7 °C
Relative humidity	42 per cent

denote the ferritic matrix which refers to decomposed and coarsened lath due to tempering. Intensive precipitates having higher hardness compared to the matrix are seen in dark contrast, since they have lower reflective index. The micrograph taken by scanning electron microscope in Fig. 1(b) supports the observations made using light microscope. The boundaries of austenite grains can be easily observed and the bainitic transformation by quenching starts from these boundaries.



(a)



(b)

Figure 1. Tempered bainite microstructure in the experimental steel after heat treatment: (a) light microscope image (b) scanning electron microscope image.

The cross-section of perforated zone after the shot is shown in Fig. 2. At the front of the steel sheet, a crater, having a certain depth and length, forms at the beginning of the penetration. It is inevitable that the armour steel fails in cleavage fracture, that means no plastic deformation, in the case of the first interaction with a projectile having high strike velocity and kinetic energy. The microstructures of the regions that are marked by alphabetical characters on the macro image are presented in Fig. 3. A typical adibatic shear band formed in the matrix of the experimental steel due to high strain by impact loading of the projectile is

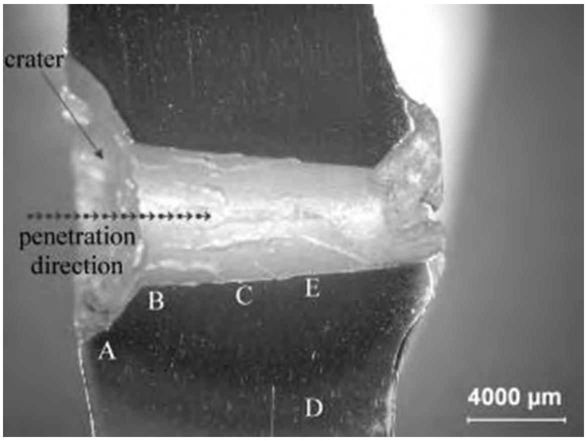


Figure 2. A macroimage of the cross-section of the perforated zone after the shot.

clearly seen in Fig. 3(a).

At high strain rates (e.g., some metal cutting operations, projectile impacts with high rates of 100-3600 m/s or fracture due to blast), materials exhibit local deformation known as adibatic shear[29,30]. Adiabatic shear bands are formed as a result of a thermomechanical instability due to the presence of a local inhomogeneity, including local deformation and heating. If the thermal conductivity of the material is not sufficient to conduct the generated heat away, deformation becomes unstable and is localised on surfaces of very small thickness (~10 µm to 50 µm). This situation is compatible in the interaction of a projectile on a steel target. High temperatures can form because of high friction of the projectile during penetration. On microscopic examination, adiabatic shear bands appear as narrow bands in which cracks can propagate, indicating catastrophic failure of the material[10]. Several models and theories have been developed to explain the occurrence of adiabatic shear bands in metals and alloys. These include phase transformation, dynamic recrystallisation, grain elongation and fragmentation, dislocation re-distribution[31]. Shear bands in different metals could be broadly classified as either 'transformed' or 'deformed' on the basis of their appearance in metallographic section.

Deformed bands are characterised by a very high shear strain in a very thin zone of deformation. Inside the band the grains are highly distorted, but there is no evident change in the structure of the material. In transformed bands, a crystallographic phase change occurs[10]. In steels, these are often called 'white bands' because of their appearance after etching, and are quite different from the matrix Fig. 3(b).

The formation of deformed and transformed ASBs in the experimental steel after shot has a similarity to the study on AISI 4340 steel, commonly used in dynamic loading test such as high strain rate test, by Bassim[31], *et al.* On the other hand, adiabatic shear band results in several perforation modes in armour steel (e.g., plugging and discing type fracture)[11]. Formed adiabatic shear bands play a role on the nucleation and subsequently on the propagation of the crack. The effect of ASB on the formation of crack will be studied in fractographical examinations. As seen in Fig. 3(c), many cracks are formed on and near the adiabatic shear band. Figure 3(d) shows the original matrix of the experimental steel, but the matrix, shown in Fig. 3(e), is degenerated due to impact loading and rapid deformation. This region has a smaller grain size than the original matrix because of strong deformation and recrystallisation. On the other hand, the degenerated microstructure behaves like strain-hardened materials.

3.2 Fractographical Examinations

The studies on the fracture surface of failed materials after static or dynamic loadings were evaluated by fractographical examinations. The loading conditions, the microstructure of the materials and external effects (e.g., ambient temperature, corrosive ambience, etc.) are very impoartant for a fractographical study (Mills, *et al.*, 1987). Figure 4 shows the scanning electron micrographs of the

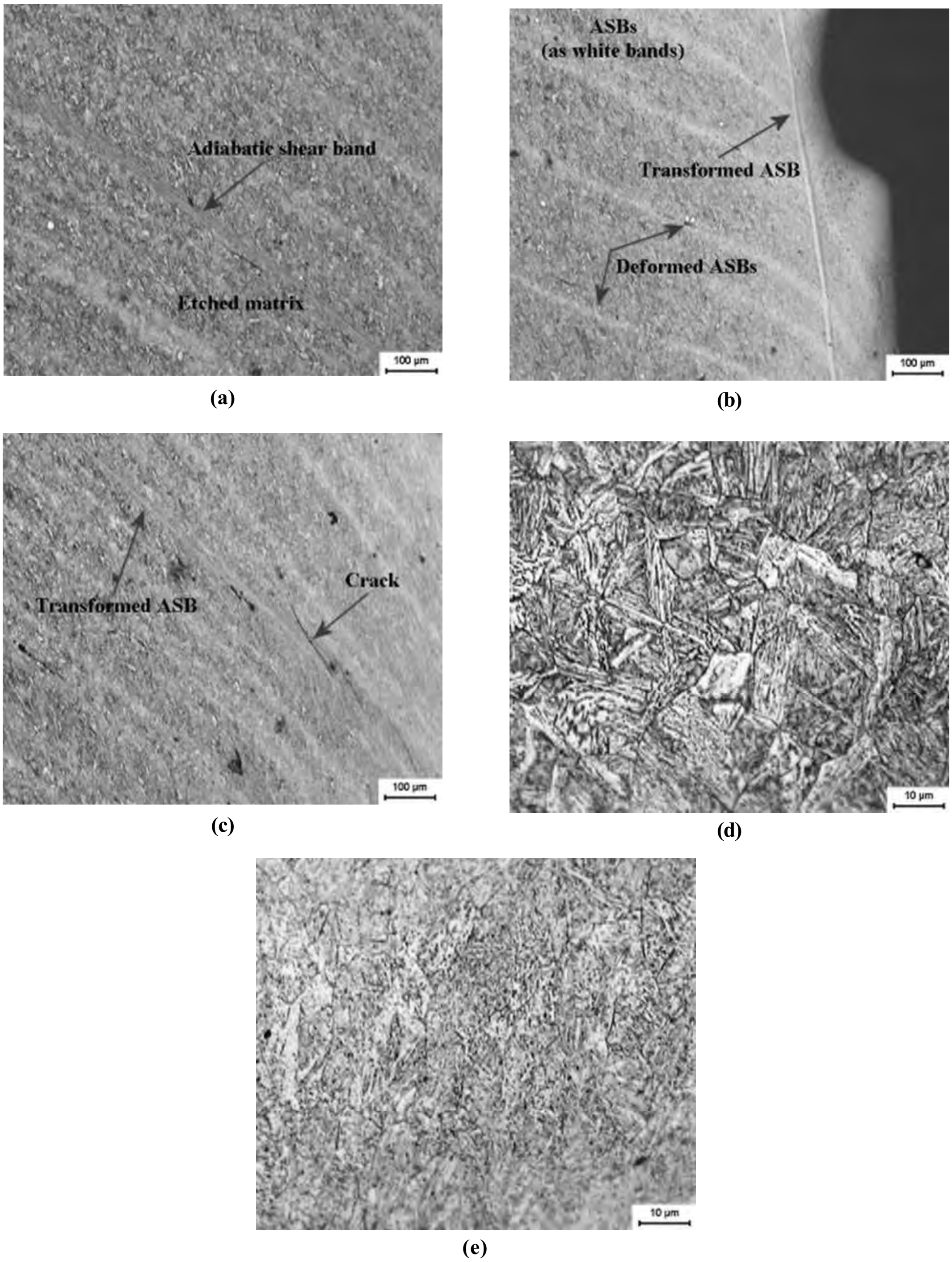
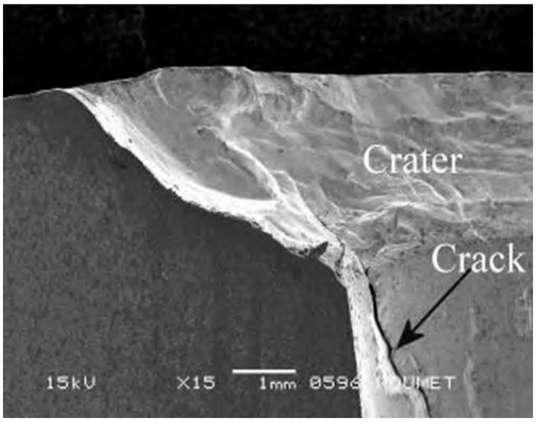


Figure 3. The microstructures of the regions marked with alphabetical characters on the macroimage in Fig. 2: (a) The structure of adiabatic shear band (ASB), (b) deformed and transformed ASBs as white bands, (c) the formation of crack-induced ASBs in the matrix, (d) the microstructure of original matrix, and (e) degenerated microstructure close to penetration.

cross-section of the perforated zone of experimental steel. Fig. 4(a) shows the crater formed at the entrance. The formation of crack due to adibatic shear bands is shown in Fig. 4(a). In general, the coalescence of the voids in the matrix or formed inhomogeneties in the matrix (e.g., dislocation pile-up, adibatic shear bands, etc.) result in failure under any kind of loading. Bassim[31], *et al.* reported for AISI 4340 steel that cracks are initiated in adiabatic shear band (ASB) leading to specimen fragmentation along the shear bands. Five stages have been identified for the process of crack initiation and propagation inside ASB's in martensitic high-strength, low alloy steels:

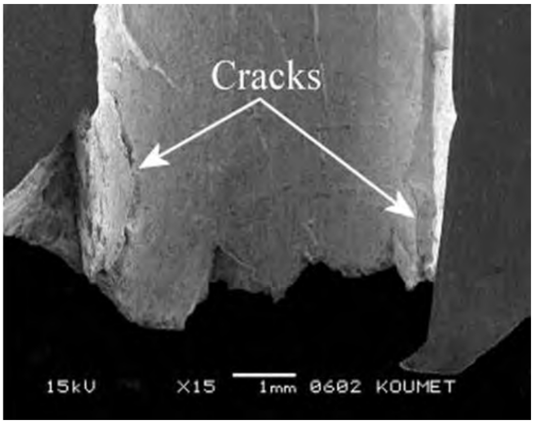
- formation of microvoids inside the shear bands,
- coalescence of these microvoids to form void-clusters which elongate parallel to the shear bands
- initiation of microcracks from the ends of the void-clusters,
- lengthwise growth and interconnection of adjacent microcracks,
- crack growth and propagation to failure[31].

At the initial step of the penetration, it is expected that the steel target fails in the cleavage fracture without any plastic deformation due to high impact loading and strain rates (Fig. 4(b)). The kinetic energy of the moving projectile is consumed as strain energy, projectile deformation energy, and frictional sliding. In this case, matrix deforms, the geometry of the projectile changes and friction forces are very effective on the formation of abrasive wear. Figure 4(b) indicates that high abrasive conditions are formed beacuse of the high friction rates between the target and the projectile during the penetration. The crack formation can be observed at the line of departure (Fig. 4(c)). The high energy of the projectile is consumed initially by the cleavage fracture and then ductile fracture. At first, the geometry of the projectile is broken and this decreases the efficiency of the projectile. This kind of formation is very important in understanding the ballistic behaviour of the armour steel. The consumption of the remaining energy of the projectile moving along the material is expected to be as plastic deformation. As seen in Fig. 4(c), there is certain elongation towards outside the target material at the line of departure. This elongation displays the intensive plastic deformation. The perforation is a typical petalling. Breakings from target steel may occur due to petalling. The variation of local hardness compared to the original matrix due to strain hardening, crack formation induced by adiabatic shear bands and the consumption of the projectile energy to cleavage or ductile fracture must be considered in the final failure formation. Thus, the hardness and toughness of the materials are very important concepts which determine the ballistic performance and the final failure formation.



(a)

(b)



(c)

Figure 4. The failure formed in the experimental steel after perforation: (a) formation of crater due to penetration of the projectile and the formation of crack because of ASBs, (b) the regions of cleavage fracture and abrasive wear, and (c) the formation of cracks at the line of departure and petalling.

4. CONCLUSIONS

In this study, the ballistic behaviour of a tempered bainitic steel has been investigated. After applied heat treatments consisting of austenisation, quenching and finally tempering, a matrix with 36 HRC hardness was obtained. The changes in the microstructure, the deformation and also perforation mode of the steel were considered after the shot performed at zero degree with a projectile velocity of 840 m/s.

The experimental steel has a tempered bainitic matrix due to applied heat treatments given in Table 2. The original matrix exhibits the decomposition of the bainite, which is transformed from austenite grain boundaries by quenching, after tempering. The original matrix was deformed due to over impact loading by the penetration of the projectile. The adiabatic shear bands and cracks near the direction of penetration were observed. The adibatic shear bands were formed as a result of the local heterogeneties, deformation and thermomechanical instability due to over heating by the friction of projectile moving along the steel. The narrow bands were characterised as 'white bands' after metallographical examinations and the cracks were formed on or close to the bands. This results in a failure as perforation or fragmentation in the steel.

The fractographical examinations on the cross-section of perforated zone after shot support the microstructural characterisation and the formation in the micro-level (e.g., the deformation, the formation of adiabatic shear bands, and cracks). The cleavage type fracture due to strain-hardened microstructure close to penetration direction was observed. The formation of the abrasive wear is inevitable under loading and motion of the projectile. The cracks due to adibatic shear bands were determined both at the first step of the projectile interaction with the steel and also at the line of departure. There is certain elongation from target material to outside at the line of departure and this elongation displays the intensive plastic deformation. The perforation is a typical petalling. Breakings from target steel may occur due to petalling.

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