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Investigation of Ricochet Angles for 5 mm Various Metal Plates with AP 7.62 Bullets

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Abstract

In this study, the effect of a high-speed AP 7.62 bullet on Ti6Al4V, AISI 4340, Inconel-718, AlSi10Mg and Al 6061 - T6 materials at different impact angles were investigated by using the finite element package software LS-DYNA 971. AISI 4340 was taken as the bullet material and 850 m/s as a speed for high-speed ballistic investigation. Angle of the obliquity of the bullet against the plates has been taken in the range of 0-80º. Simulations were carried out at 5 degrees increments. It has been investigated that at what angle the bullet touches the materials, the bullet will ricochet. Also, deformations on plates have been examined. The results showed a good correlation with the literature. The lowest ricochet angle has been obtained in Inconel-718 as 20 º followed by AISI 4340 as 25º, Ti6Al4V as 55º, Al 6061 - T6 as 75º and lastly AlSi10Mg as 80 º.

Keywords: Ricochet, penetration angle, residual velocities, ballistic limit, oblique impact

1. INTRODUCTION

Aluminum alloys are frequently used in light armor applications in the defense industry due to their physical and mechanical characteristics, low density, high strength, and high energy absorption capacity [1]. Although the strength of aluminum is lower than steel, more strength can be obtained with dimensional changes in thickness or diameter compared to steel. Despite the growth in dimensions, the low density of aluminum, the total weight of these materials is lower than that of steel materials.

Aluminum and its alloys extensively have been investigated in the past studies for ballistic purposes. Bullet geometry, penetration angle, ballistic limit, and residual velocities are some of the research topics of armor applications. Bullet penetration angle is one of the most important parameters for the perforation of the armor. When the bullet reaches the critical obliquity angle, the bullet doesn’t perforate the target, and it ricochets.

Özer et al. investigated the effects of thicknesses of Titanium, Ti6Al4V, and AISI 4340 materials against different bullet geometries. It was seen that the least deformation encountered in AISI 4340 [2].

Iqbal et al. [3] studied the effect of Blunt-nosed, Ogive-nosed, Hemispherical-nosed projectile on

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the single and layered aluminum plate. They have found that aluminum plates for all different thicknesses have the highest ballistic resistance for Hemispherical-nosed projectile. In another study of Iqbal et al. [4], they have used ogive nosed projectile and 1100-H12 aluminum targets to examine the effect of penetration angle. They demonstrated that the ballistic limit of aluminum target increased with the increasing obliquity.

Piekutowski et al. [5] have used 6061-T651 aluminum plates and 4340 ogive-nose steel rods to perform perforation experiments. They have carried out normal and oblique impacts on plates to evaluate residual velocities and perforation. Finally, they came up with a perforation equation, which precisely estimates the ballistic limit and residual velocities. Gupta et al. [6] have examined the effects of the nose shape and velocity of the bullet and target thickness, blunt and hemispherical nose on bullet impact on aluminum plate. In addition, they demonstrated that hemispherical nose-shaped bullets had more ballistic limits than blunt. Zaid Mohammad et al. [7] presented the effect of the angle of obliquity on single layer and double layered 2 mm-thick 1100-H12 aluminum material, in both set-up, hemispheric nose have showed higher ballistic resistance. Corbett et al. [8] conducted experimental studies and revealed that low obliquity below 30º didn’t affect the ballistic limits and behavior of the target. But obliquity greater than this value increased the ballistic limits, so the resistance of the target significantly increased.

Bhuarya et al. [9] studied the ballistic effect of bullet hitting on aluminum alloy with different angles and thicknesses. They have examined critical thickness and angle values for perforation, ricochet and embedment.

Børvik et al. [10] used different types of bullets to examine the effect of penetration to a 20 mm thick AA6082-T4 aluminum plate with different penetration angles. Hardcore bullets velocity drop doesn’t affect penetration angle up to 30º. But soft-core bullets have a decreasing trend in velocity with increasing angle. Above 30º and below the 60 º velocity drops were considerable. At 60º penetration, none of the bullets was able to penetrate the target plate. In literature, single-layer aluminum plates were found to be more resistant to bullet impact than layered aluminum plates. While thin plates (0,5 mm - 1.5 mm) are more resistant to the impact of blunt-nosed projectile, thick plates (2 mm - 3 mm) leaded to better resistance to the effect of ogive-nosed projectile [3, 11]. Similar studies have been conducted by Gupta et al. [12]. These studies demonstrated that for thin plates (0.5 mm - 1.5 mm), the most efficient penetrator was ogive nosed projectile. For thick plates (2 mm - 3 mm) blunt-nosed projectiles required the least energy to perforate the target plates.

Zhou et al. [13] studied the effects of obliquity and projectile shape on the ballistic limit of a single layer, double-layered, and sandwiched steel plates. Flat nosed projectile causes a higher ballistic limit on layered plates, however, when it comes to hemispherical nosed projectile no significant differences are observed on the ballistic limit. With increasing obliquity, firstly ballistic limit demonstrated a decrease and subsequently increasing tendency. For both projectile shapes and layer numbers, the lowest

Table 1
Johnson Cook Parameters of used materials in FEM analyze

JC parameters	Yield stress, A (MPa)	Strain hardening parameter, B (MPa)	Strain hardening exponent, n	Strain rate sensitivity parameter, C	Temperature exponent, m	D1	D2	D3	D4	D5
Al6061 T6	324	113.8	0.42	0.002	1,34	-0.77	1,5	-0.47	0	1,6
AlSi10Mg	167	396	0,551	0,001	0,859	0,047	1,155	-0,841	-0,042	0
Ti6Al4V	1000	331	0.34	0.012	0,8	-0.09	0,25	-0.5	0.014	3,9
4340 Steel	793	510	0.25	0.14	1,3	0,05	3,4	-2.12	0.002	0.61
Inconel-718	985	949	0.4	0.01	1,61	0.04	0.75	-1.45	0.04	0.89

ballistic limit was seen at penetration angles between 30º and 45º.

AlSi10Mg is manufacturable material in SLM. Its properties of lightweight and high energy absorbability per mass makes it researched. Kristoffersen et al. [14] investigated the ballistic limit of 5mm SLM manufactured AlSi10Mg plates. They use both experimental tests and numerical analyses. Nirmal at. Al.[15] found Johnson-Cook strength ad damage parameters via Split-Hopkinson pressure bar setup. Then, they use these parameters to investigate ballistic parameter of AlSi10Mg plates.

Israr ul Haq et al.[16] and Marcos Rodríguez-Millán et al. [17] investigated effects of the nose tip angle (geometry) of bullet which penetrate to Inconel-718 plate. They showed geometry affected the deformation mode of the Inconel-718 plate and ballistic limit significantly.

Borja Erice et al. [18]have researched effects of the temperature of Inconel-718 plate on ballistic performance when impacted by spherical projectiles. J. Michael Pereira [19] have researched the effects of the annealing and aging processes on the ballistic performance of the materials. Annealing and aging have yielded difference in strength and toughness which greatly influenced the ballistic performance.

In literature several research can be found related to ballistic research on Inconel-718. But there aren't enough researches to evaluate the ricochet angle for Inconel-718. In this research, we have aimed to investigate the ricochet angle of bullet penetrates to Inconel-718 plate with different angle and test result compared with common armor materials.

In this study, we aimed to investigate ricochet angle occurred in high-speed bullet penetration to different material in the oblique impact of AP 7.62 bullets. Additionally, additively manufactured AlSi10Mg and novel Inconel-718 nickel alloy's ballistic performance have been investigated and compared with the traditional ballistic materials, AISI 4340 as 25º, Ti6Al4V as 55º, Al 6061. We employed the finite element package software LS-DYNA 971. Plate thickness and bullet velocity were kept as 5 mm and 850 m/s respectively in all test samples. The angle of obliquity was increased gradually with 5 degrees increments up to ricochet.

2. METHODOLOGY

Ballistic performance effect on bullet pitch angle, target plate thickness and target plate material were investigated. AP 7.62 bullet was chosen as a projectile and the initial velocity was 850 m/s. This velocity was chosen because it was the average velocity for AP 7.62 bullets [20]. The size of the target was 10cmx10cm in size, 5mm in thickness in Figure 1. Angle of obliquity was taken in the range 0-80 º.

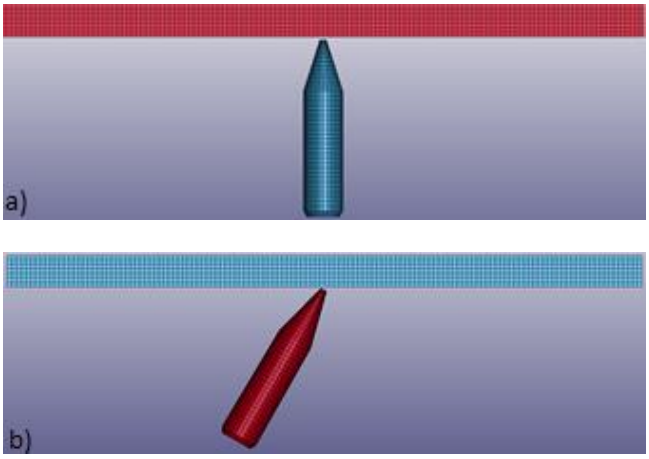

Figure 1 Mesh of the bullet and target at different obliquity angles.

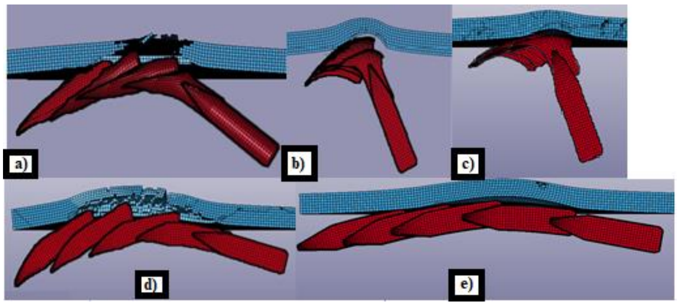

Figure 2 Ricochets of bullets for Ti6Al4V (a), AISI-4340 (b), and Inconel 718(c), Al 6061 - T6 (d), and AlSi10Mg (e) plates.

In this paper, ballistic numerical simulations were made in LS-DYNA 971 which is an explicit solver of the non-linear finite element method. Previous studies have shown that this program simulates ballistic performance very well [21, 22]. Johnson Cook Model (MAT_15) was used for strength and damage evolution for ductile materials. The eqs. (1)-(3) shows the fracture criteria, damage parameters and failure damage[15, 23, 24]. Johnson Cook (JC) model simulates a von Mises plasticity, initial yielding, linear elasticity, strain hardening, strain-rate hardening, damage evolution and fracture. This model predicts equivalent stress with using of temperature, strain rate and strain parameters:

$$\sigma(\varepsilon,\dot{\varepsilon},T) = [A + B\varepsilon^n]\left[1 + C\,ln\frac{\dot{\varepsilon}}{\varepsilon_{ref}}\right]\left[1 - \left(\frac{T-T_0}{T_m-T_0}\right)^m\right] \qquad (1)$$

A, B, n, C and m are yield stress, strain hardening parameter, strain hardening exponent, strain rate sensitivity parameter and temperature exponent respectively. T0, Tm are a reference and melting temperature. ε_ref is reference strain rate.

Fracture strain for Johnson-Cook Model depends on the stress triaxiality, strain rate and temperature:

$$\varepsilon_f(\sigma^*,\dot{\varepsilon},T) = \left[D_1 + D_2e^{D_3\sigma^*}\right][1 + D_4 ln\dot{\varepsilon}]\left[1 + D_5\frac{T-T_0}{T_m-T_0}\right] \qquad (2)$$

where D1 - D5 are fracture model constants of the Johnson-Cook model, σ* is the stress triaxiality ratio.

Damage evolution keeps zero during elastic region. After some certain threshold of the accumulated plastic strain, damage evolves. The equation of Johnson Cook damage evolution is:

$$\dot{D} = \begin{cases} 0, & \varepsilon < p_d \\ \frac{D_c}{\varepsilon_f - p_d}\dot{\varepsilon}, & \varepsilon \geq p_d \end{cases} \qquad (3)$$

Pd is the damage threshold, ε_f is fracture strain and Dc is the critical damage. When D reaches to 1 then the element is deleted and removed from calculation.

Johnson Cook parameters of AISI 4340-H steel alloy, Al6061-T6, Ti6Al4V, AlSi10Mg and Inconel-718 are Table 1. JC material parameters and Equation of State parameters are taken from these studies [25-32]. Materials assumed anisotropic. 3D cad model used for solid with full of hexagonal mesh.

Hourglass IHQ=5 and QH=0.1 is used for energy control. The plates are fixed from bottom edges. ERODING_SURFACE_TO_SURFACE eroding algorithm is used with 0.3 static friction and 0.2 dynamic friction and pinball segment-based contact (SOFT=2). Maximum mesh size 0.75mm is used and total number of elements is 180000.

3. RESULT AND DISCUSSION

When evaluating simulation results in Figure 3, bullet deformations were lowest for aluminum targets at each angle and bullet penetrates until ricochet angle. Also, the Von-Misses stresses on the plates were shown in the same figure. For steel and Inconel plates, they showed bulletproof at each angle. Steel and Inconel plates had better ballistic performance at the same volume in these material options. The ricochet angle of steel was found to be 25º and that of Inconel was 20º. Impact results and residual velocity were presented at Figure 3 and at Figure 4 respectively. With increasing bullet angle, deformation on target were decreased. Bullets deformation was the highest at steel plates followed by Inconel, titanium and aluminum alloys. For comparison, the normal impact, 15˚ and 30˚ were investigated for all materials, but the result of 15˚ for aluminum alloys weren't added to the figure; because aluminum alloys didn't show much difference in deformation between 0˚ and 30˚.

Titanium has higher yield strength than steel but steel has better ballistic performance because the first thing to check for ballistic performance is hardness[33] and density. Hardness is needed to deform the bullet; the kinetic energy of the bullet should be absorbed in deformation mechanisms and one of the deformation mechanisms is the deformation of the bullet that absorbs kinetic energy. Also, density has significant effect on deformation of bullets. Titanium has lower density and hardness value than Inconel and steel. Therefore, Inconel and steel are better bullet-proof materials in same volumes. Material strength affects ballistic performance after density and hardness.

For titanium plates, it has a higher ballistic limit and better ballistic performance against aluminum alloys, however steel bullet still penetrates until the ricochet angle. In Figure 3, it is seen that some erosions on steel bullet. The bullet is stacked at 50º, but it has a residual velocity at 55º. Therefore, 55º is chosen for ricochet angle in this situation. When the residual velocities are examined, there is a continual decrease until 50º, residual velocity increases after that angle.

To compare residual velocities for different materials, Figure 4 (a) was presented below. In the figure, the highest residual velocities emerged in AlSi10Mg at ricochet angle. Kinetic energy greatly was absorbed by AISI 4340 and Inconel. This can be concluded that AlSi10Mg has lowest density and hardness values in this research.

According to G. Tiwari et al. 's study [34], ricochet angle is changing with the target thickness, target span, bullet nose geometry and bullet velocity. Because of the influence of so many parameters to ricochet angle, it is difficult to compare the results of different studies. In G. Tiwari's study, the ricochet angle is found around 60 degrees for 1mm 1100-H12 aluminum plates and at low velocities (less than 200 m/s) with ogive nosed bullet, which shows that our aluminum ricochet angle result is in accordance with the literature.

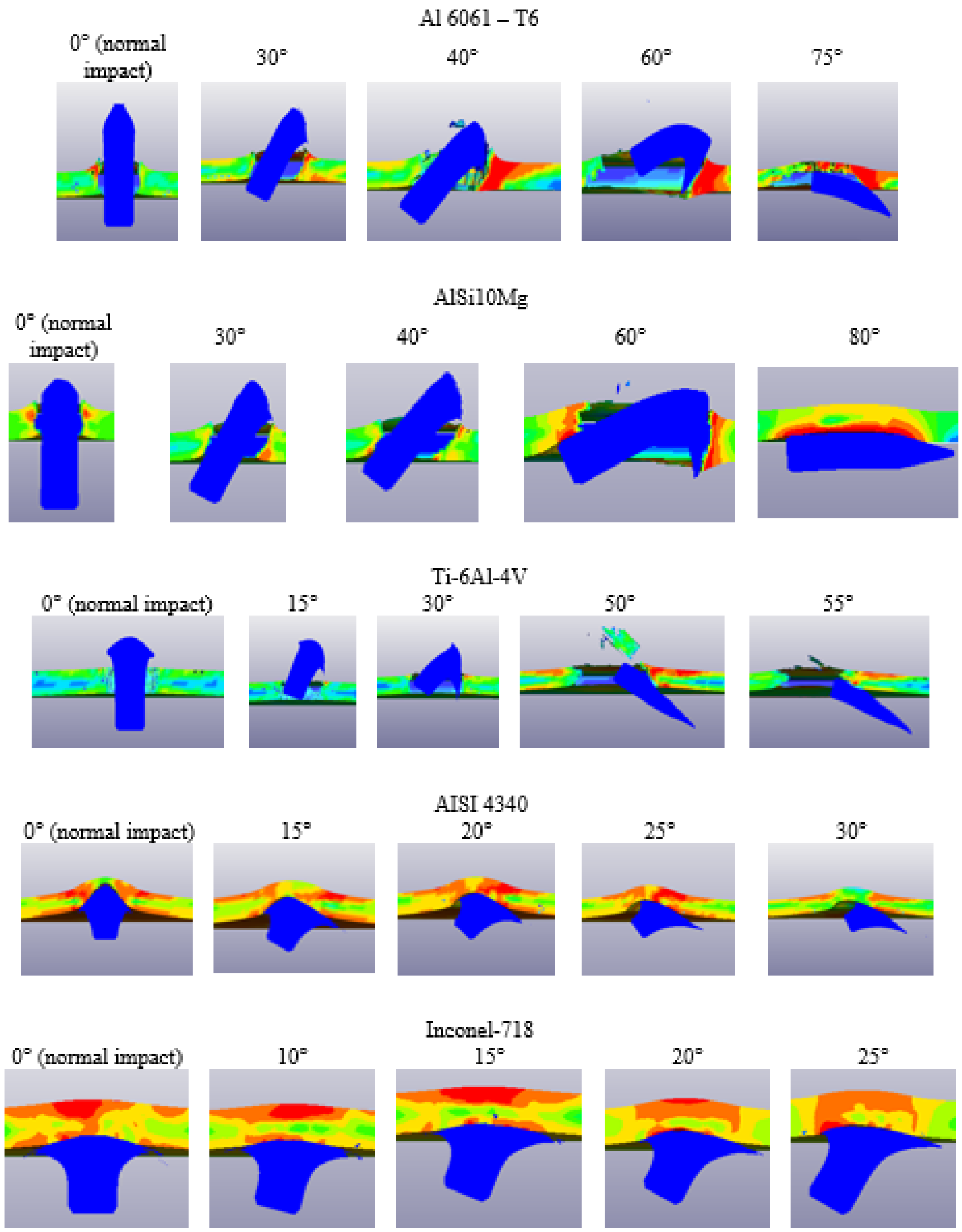

Figure 3 Impact results at different angles for different materials

Residual velocities of the bullets at different angles are presented in Figure 4 from (b) to (f). Looking at the test of aluminum alloy plates at different angles, there is a continuous decrease at residual velocity with increasing pitch angle until ricochet angles. At 75° for Al6061 and 80° for AlSi10Mg, it is seen that residual velocity is higher than 70° and 75° impacts, so 75° for Al6061 and 80° for AlSi10Mg are the ricochet angle for a 5 mm aluminum alloy plates. This high angle is reasonable because it sorts together with experimental ricochet tests. Aluminum is a soft material when compared to steel, therefore aluminum gets eroded easily. The density and hardness difference between AlSi10Mg and Al6061 are considerably low, the material strength and damage parameters taken literature; therefore, it is unclear whether the cause of the allistic difference is the alloy itself or the heat treatment difference. Aluminum also has the lowest yield and tensile properties than steel and titanium have. In Figure 2, the bullet has ricocheted in steel without too much damage while aluminum deforms easily. Also, Al6061 has some cracks inside after impact.

It is concluded that the ricochet angle was increased with material hardness or density decreased with looking aluminum alloys, steel, Inconel and titanium plates. FEM JC material model was managed to catch the relations. Also, time interval 80 µs for simulation was sufficient converge to equilibrium.

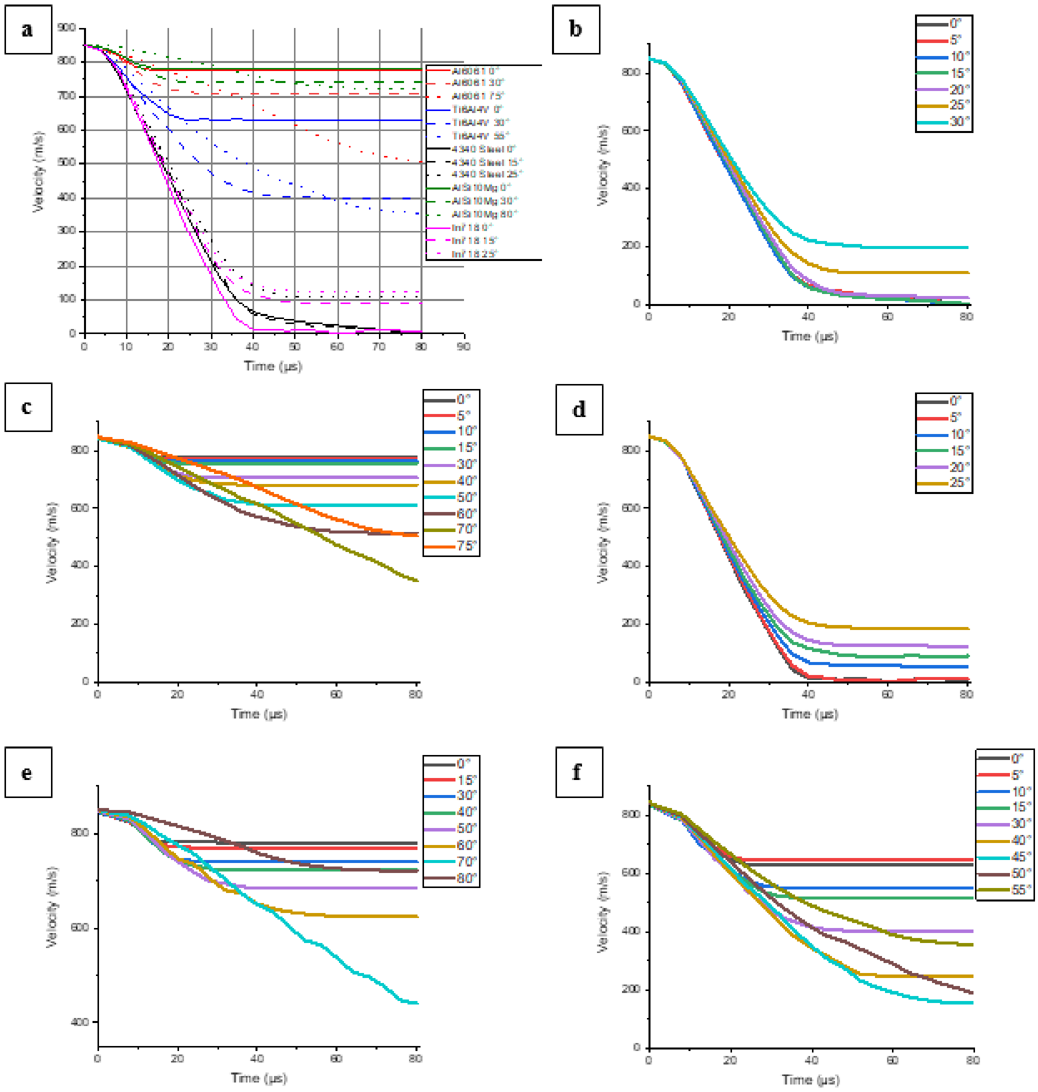

Figure 4 a) Comparision of the residual velocities with respect to time and materials and b), c), d), e), and f) residual velocities at different angles for AISI4340, Al6061, Inconel718 and AlSi10Mg and Ti6Al4V plates, respectively.

4. SUMMARY

In this article, during the bullet penetration to different materials, titanium, steel, Inconel, Al6061 and AlSi10Mg ricochet angles were investigated by using finite element package software LS-DYNA 971. Ricochet angles were found 20º for Inconel-718, 25º for AISI4340, 55º for Ti6Al4V, 75º for Al6061 and 80 º for AlSi10Mg. The ballistic performance of these materials is discussed. The results showed a good correlation with the literature.

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The Declaration of Conflict of Interest/ Common Interest

No conflict of interest or common interest has been declared by the authors.

Authors' Contribution

The authors contributed equally to the study.

The Declaration of Ethics Committee Approval

This study does not require ethics committee permission or any special permission.

The Declaration of Research and Publication Ethics

The authors of the paper declare that they comply with the scientific, ethical and quotation rules of SAUJS in all processes of the paper and that they do not make any falsification on the data collected. In addition, they declare that Sakarya University Journal of Science and its editorial board have no responsibility for any ethical violations that may be encountered and that this study has not been evaluated in any academic publication environment other than Sakarya University Journal of Science.

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