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Investigation of Ballistic Impact Response of Aluminum Alloys Hybridized with Kevlar/Epoxy Composites

Araştırma Makalesi / Research Article

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ABSTRACT

In this comparative study, ballistic impact responses of various aluminum alloys hybridized with Kevlar/Epoxy composite is investigated numerically. The numerical models were developed using the explicit finite element module of ANSYS. 50 caliber projectile with an initial velocity of 400 m/s is used during the analyses. In the first part of the study, 7075, 6061 and 2024 aluminum alloys are compared for their ballistic impact resistance. Amount of perforation energies (energy absorbing capacity of target) and projectile residual velocities of these alloys are compared. Also, thicknesses of plates are increased up to the point at which the plates don't exhibit full perforations for the used projectile and initial velocity. It is seen that that residual velocity of the Al 7075 T6 is the smallest among the used aluminum alloys which means that 7075 T6 type of aluminum has the higher ballistic impact resistance. In the second part of the study, six different hybrid models that have different combinations of Al 7075 and Kevlar29/Epoxy are proposed. Perforation energies and projectile residual velocities of these proposed models are compared under ballistic impact loadings. It was shown that the hybrid model with 6AL-6KEV orientation, was the optimum structure to resist the ballistic impact loading among the proposed models. Which means that the plate with this orientation has exhibited the maximum energy absorbing characteristics.

Keywords: Ballistic impact, aluminum alloys, kevlar.

Kevlar / Epoksi Kompozitleri ile Hybrid Yapılan Alüminyum Alaşımlarının Balistik Darbe Tepkilerinin Araştırılması

ÖZ

Bu karşılaştırmalı çalışmada, Kevlar/Epoksi kompoziti ile hybrid yapılan çeşitli alüminyum alaşımlarının balistik darbe davranışları numerik olarak araştırılmıştır. Numerik modeller, ANSYS'in eksplisit sonlu elemanlar modülünü kullanarak oluşturulmuştur. Analizler sırasında başlangıç hızı 400 m/s olan 50 kalibrelik mermi kullanılmıştır. Çalışmanın ilk bölümünde, 7075, 6061 ve 2024 alüminyum alaşımları, balistik darbe dayanımları açısından karşılaştırılmıştır. Bu alaşımların perforasyon enerjileri miktarları (hedefin enerji absorbe etme kapasitesi) ve mermi son hızları karşılaştırılmıştır. Ayrıca, plakaların kalınlıkları, kullanılan mermi ve başlangıç hızı için plakaların tamamen perfore olmadığı noktaya kadar arttırılmıştır. Al 7075 T6'nın son hızının kullanılan alüminyum alaşımları arasında en küçük olduğu görülmektedir, bu da 7075 T6 alüminyumun daha yüksek balistik darbe dayanımına sahip olduğu anlamına gelmektedir. Çalışmanın ikinci bölümünde, Al 7075 ve Kevlar29/Epoksi'nin farklı kombinasyonlarına sahip altı farklı hibrid model oluşturulmuştur. Bu oluşturulan modellerin balistik darbe yükleri altında perforasyon enerjileri ve mermi son hızları karşılaştırılmıştır. Elde edilen sonuçlar 6AL-6 KEV hibrid modelin, önerilen modeller arasında balistik darbe yüküne dayanım açısından en uygun yapı olduğunu göstermektedir. Bu sonuç, bu modelin balistik darbe yükleme koşulları altında maksimum enerji absorbe edebilme özelliğine sahip olduğu anlamına gelmektedir.

Anahtar Kelimeler: Balistik darbe, aluminyum alaşımları, kevlar.

1. INTRODUCTION

Structures are exposed to the various loads during the operating conditions. Ballistic impact loads are the most critical loads which the structures may be exposed. Hence, ballistic impact capacities of different materials are an important research area and have been studied by the many researchers. During the normal impact events, forces on the target structures can be assumed as distributed (on a small area) on the impact zone. But, in the ballistic case, forces are concentrated on the points of impacts which causes high deformations and stresses at these points. Residual velocities defined as the final velocity of the projectile after impact, and perforation energies defined as the energy which can be absorbed by the target plate during full or partial penetration of the targets are important parameters to compare different materials. So, on the many of these studies [1-5], the aim was to find a material or material combinations to prevent penetration of targets under the high impact velocities.

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Nowadays the researchers started to investigate to find light-weight materials which can have high impact load absorbing capacities with less weights. Hence, some metallic materials and composite materials can have the solution for this issue since they have high specific strength and modulus. Aluminum alloys are one of the solutions for this issue and studied by some of the researchers [6-15].

During the impact event, different mechanical properties of materials can be effective like yield and ultimate strength, hardening parameters [16], the toughness of resin [17] for the composites. It was also proved by experimentally and numerically that some of the polymer matrix composites show unique properties under the effects of the impact loadings. So, there are many investigations that are showing this fact. Carbon/Epoxy [18-24], Glass/Epoxy-polyester [25-28], Kevlar/Epoxy-Vinylester [29-40] polymer composites are mainly studied ones. Among the fibers of the polymer matrix composites, Kevlar is an important material since this material type have high impact load absorbing capacities and have been an important researched fiber type. Sandwich composites which are the combinations of Glass fiber and Kevlar/epoxy was studied by Ansari et al. [40]. Ballistic impact characteristics of a Kevlar/Epoxy helmet were investigated considering deformation, stress, final velocity and acceleration using hydro-code simulations of AUTODYN by Tham et al. [32]. Kumar et al. [34] performed numeric analyses to predict the ballistic resistance of Kevlar-Epoxy composites using 100-1000 m/s velocities. Influences of friction on the ballistic response of aramid fibers were investigated by Briscoe et al. [30].

Composite materials are the important material types and many of the properties are unique and new material properties can be achieved by the optimization[41] or the combination of different fibers. Different combinations of various materials that have unique properties are one of the effective ways to improve the mechanical properties of the materials. This process is called as hybridization and has been an important choice for many applications. Hybridization is also can be used to improve the energy absorption capacities of materials and some of the researchers have been investigated this issue. Naik et al. [18] studied hybridization effects of glass–carbon/epoxy polymer composites on the Impact loadings. Shape memory alloy and Spectra hybridization was investigated by Ellis et al. [42]. Pereira et al. [33] studied impact characteristics of Kevlar 49 and Zylon. Randjbaran et al. [38] studied effects of hybrid materials that are formed using Kevlar-Carbon-Glass fibers for Ballistic Impact Testing. Silva et al. [22] studied impact characteristics of hybrid carbon-epoxy/cork composites. E glass and Kevlar 29 fibers are hybridized by Muhi et al. [43] and ıt was shown that with the addition of Kevlar layers penetration resistance was increased.

In this study, ballistic impact response of various aluminum alloys hybridized with Kevlar/Epoxy composite is investigated numerically. The study has two main parts. In the first part of the study, ballistic impact analyses of 7075, 6061 and 2024 aluminum alloys are performed and the result of these analyses are compared for their ballistic impact resistance. During this comparison the amount of perforation energies (energy absorbing capacity of target) and projectile residual velocities are considered. Also, thicknesses of plates are increased up to the point at which the plates aren't exhibited full perforations for the used projectile and initial velocity. In the second part of the study, Al 7075 (which has maximum ballistic load absorbing capacities among the used aluminum alloys, and this is shown by the results of the first part of the study) and Kevlar 29/Epoxy are combined in the various combinations. Six different hybrid models that have different combinations of Al 7075 and Kevlar29/Epoxy are proposed. Perforation energies and projectile residual velocities of these proposed models are compared under ballistic impact loadings.

2. NUMERICAL STUDIES

In this study, ballistic impact responses of various aluminum alloys hybridized with Kevlar/Epoxy composite are investigated numerically. The numerical models were developed using the explicit finite element module of ANSYS. The analyses were performed using the Lagrangian approach available in ANSYS.

The geometry of the projectiles are important and the shape of the projectile affects the amount of perforation energy. In this study, 50 caliber projectile (sharpen tip[44]) whose geometrical properties are given in Figure 1 is used. The mass of the used projectile equals to 46.16 g.

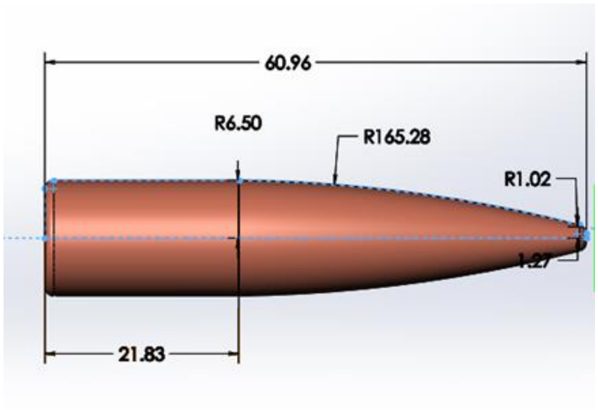


Figure 1. The projectile geometric information (dimensions in mm)

In the first part of the study, 7075, 6061 and 2024 aluminum alloys are compared for their ballistic impact resistance. Projectile residual velocities and amount of perforation energies (energy absorbing capacity of The argets) of these alloys are compared. mechanical properties of used alloys are given in Table 1.

Table 1. Mechanical properties of Aluminum alloys

Material	S_{yi} (Mpa)	S_{ymax} (Mpa)	Hardening exponent n	E (Gpa)	G (Gpa)	v	ρ (kgm^{-3})
Al 7075 T6	420	810	0.113	72	26.70	0.3	2804
Al 6061 T6	290	680	0.110	70	27.60	0.3	2703
Al 7075 T8	260	760	0.160	73	28.60	0.3	2785

The boundary conditions of models are given in Figure 2. During the analysis, the projectile is considered as rigid and an initial velocity of 400 m/s is applied as seen in Figure 1. The target plate is fixed from all edges.

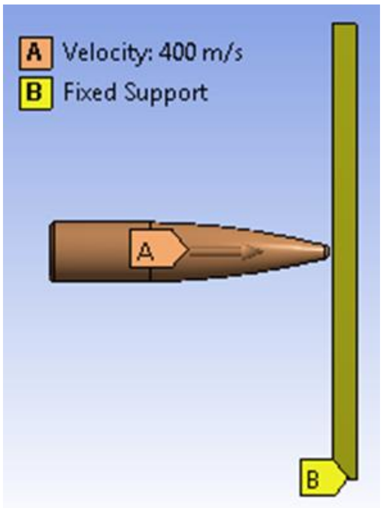


Figure 2. The boundary conditions

2.1 Mesh Convergence Analysis

Before the numerical study, the accuracy of the mesh is controlled doing a mesh convergence analysis. Eight different mesh sizes (element sizes) varying from 0.3 mm to 5 mm were selected and analyzed for AL 7075 T6 and 1 mm plate thickness. Mesh comparison for Al 7075 T6 considering the projectile velocity reduction during ballistic impact for this plate is given in Figure 3. It was shown that the element size less than 0.6 mm was converged to the residual velocity. During the analyses, 0.5 mm element size is used.

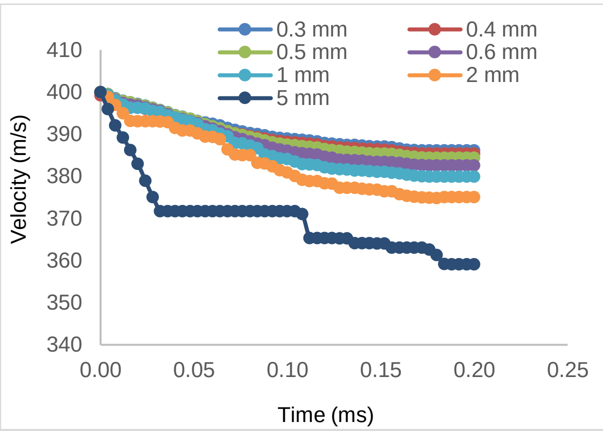


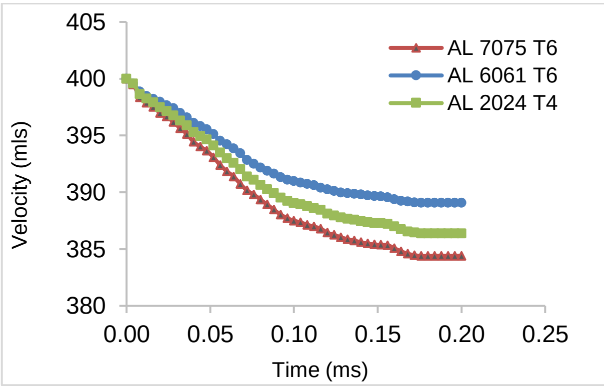
Figure 3. Mesh comparison for Al 7075 T6

3. RESULTS AND DISCUSSION

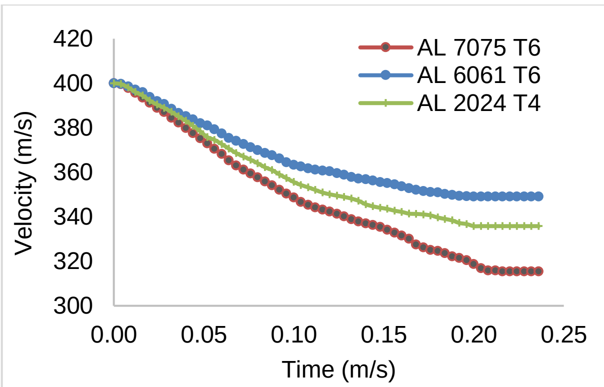
Results are given in the two section. In the first section of results and discussion, the ballistic impact responses of the aluminum alloys are given. In the second section, the ballistic impact responses of the hybrid models are given.

3.1 Ballistic Impact Responses of Aluminum Alloys

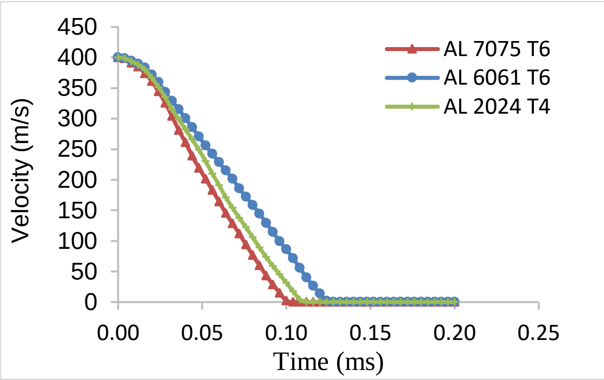
As mentioned in the previous sections, in this study firstly ballistic impact responses of Al 7075 T6, Al 6061 T6 and 2024 T4 are compared. Projectile velocity reductions during ballistic impact for these aluminum alloys are given in Figure 4. It shows that the residual velocity (the velocity of the target after full or partial perforation of the target, this velocity decreases to the zero if the target cannot be perforated fully) of the Al 7075 T6 is the smallest among the used material types. For 5 mm thickness of the target plate, the residual velocity of the Al 7075 T6 is approximately 9.6 % smaller than the residual velocity of the Al 6061 T6. In the case of the partial perforation of the target, when the thickness is equal to 15 mm, it is seen that the velocity of projectile decrease to zero the earliest (approximately 20 %) among the used material types.



(a)



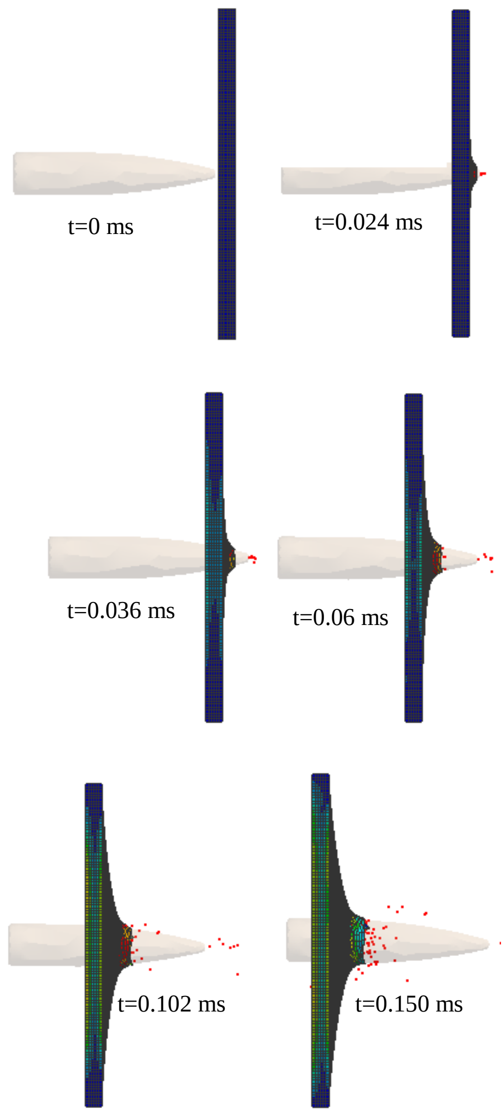
(b)



(c)

Figure 4. Projectile velocity reduction during ballistic impact for the different aluminum alloys a) 1 mm thickness, b)5mm thickness, c)15 mm thickness

Damage propagation on the 5 mm target plate with AL 7075 T6 material type for ballistic impact loading is given in Figure 5. It is seen that perforation is starting when time equals to the 0.024 ms, and this plate is fully perforated after 0.2 ms.



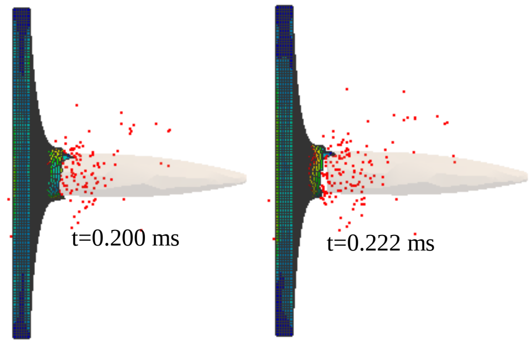


Figure 5. Damage propagation on the 5 mm target (AL 7075 T6) for ballistic impact loading (Vi = 400 m/s)

Also, thicknesses of plates are increased up to the point at which the plates aren't exhibited full perforations for the used projectile and initial velocity. In Figure 6, projectile velocity reduction during ballistic impact for the different thicknesses of AL7075 T6 is given. The thickness of the target plate is increased to 15 mm from 1 mm. It is seen that with the increase of the thickness of target plate, amount of the residual velocity is decreased and when the thickness equal to the 15 mm, the velocity of the projectile is decreased to zero. Which indicates that there is not full perforation of the target at this situation.

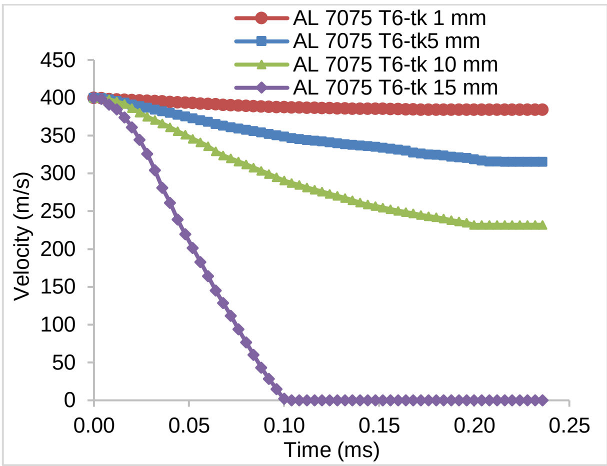


Figure 6. Projectile velocity reduction during ballistic impact for the different thicknesses of AL7075 T6

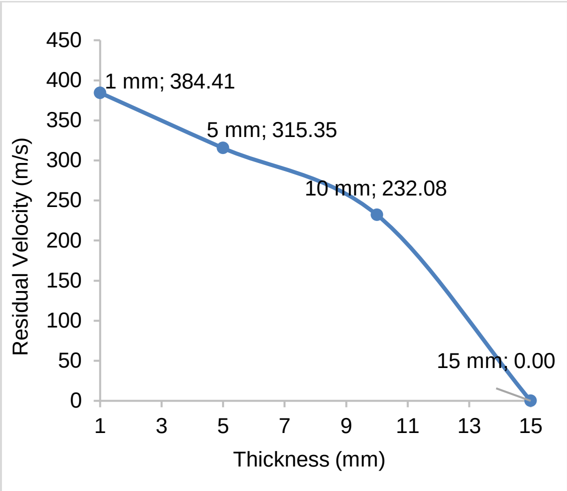
The energy absorption of target plates is also compared in this study. The energy absorption capacities (EAbs) of plates are calculated using the following equation:

$$E_{Abs} = \frac{1}{2} m_p (V_i^2 - V_r^2) \qquad (1)$$

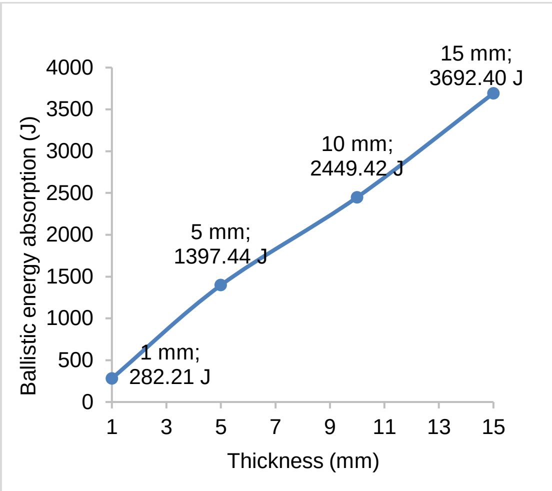
Where;

E_{Abs}= Energy absorption by the target (J); mp= mass of the projectile (kg); Vi= initial velocity of the projectile (m/s); Vr= final (residual) velocity of the projectile (m/s).

The residual velocity of the target with Al 7075 T6 material type is given in Figure 7(a) and Table 2, amount of absorbed energy comparison of this model is given in Figure 7(b) and Table 2. The figure and the Table show that with the increase of the thickness to 15 mm from 1mm, the residual velocity is decreased 0 m/s from 384.41 m/s. And amount of absorbed energy is increased to 3692.40J from 282.21 J.



(a)



(b)

Figure 7. Variation of (a) Residual velocities (b) Energy absorptions of AL 7075 T6 for different thicknesses

Table 2. Residual velocities and Energy absorptions of AL 7075 T6 for different thicknesses

Thickness (mm)	Residual velocity (m/s)	Ballistic energy absorption (J)
1	384.41	282.21
5	315.35	1397.44
10	232.08	2449.42
15	0.00	3692.40

*$V_{initial}$=400m/s

Table 3. Mechanical properties of Kevlar29/Epoxy[45]

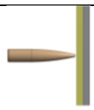
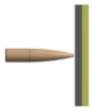
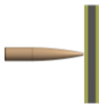
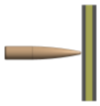
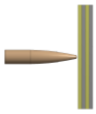
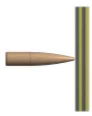
S_{Xt} (Mpa)	S_{Xc} (Mpa)	S_{Xc} (Mpa)	S_{yc} (Mpa)	E_1 (Gpa)	E_2 (Gpa)	E_3 (Gpa)	G_{12} (Gpa)	G_{13},G_{23} (Gpa)	ν_{12}	ν_{13},ν_{23}	ρ (kgm^{-3})
1850	185	185	185	18.50	18.50	6.00	0.77	5.43	0.25	0.33	1440

3.2 Ballistic Impact Responses of Aluminum Alloys

Kevlar29/Epoxy, its mechanical properties are given in Table 3, is an extensively used material type (as discussed in the introduction section) for the ballistic impact protective structures. And it is seen in the first part of the study that Al 7075 T6 has the maximum energy absorption among the used aluminum alloys in this study.

In the second part of the study, six different hybrid models with different combinations of Al 7075 T6 and Kevlar29 /Epoxy were proposed. These models are all 12 mm thick and consist of different aluminum and Kevlar combinations. These combinations are 6KEV + 6AL, 6Al + 6KEV, 3KEV + 6Al + 3KEV, 3AL + 6KEV + 3AL, 3KEV + 3AL + 3KEV + 3AL and 3AL + 3KEV + 3AL + 3KEV. And these combinations are named as H1, H2, H3, H4, H5 and H6 as shown in Table 4

Table 4. Schematic representation of different hybrid models

Model	Geometry	Individual thickness (mm)	Total Thickness (mm)
H1 (6KEV + 6AL)		6+6	12
H2 (6AL+ 6KEV)		6+6	12
H3 (3KEV + 6Al + 3KEV)		3+6+3	12
H4 (3AL + 6KEV + 3AL)		3+6+3	12
H5 (3KEV + 3AL + 3KEV + 3AL)		3+3+3+3	12
H6 (3AL + 3KEV + 3AL + 3KEV		3+3+3+3	12

Perforation energies, projectile residual velocities of these proposed models are compared for the ballistic impact loadings in Figure 8. It has been shown that the target plate which formed having 6AL-6KEV orientation has the minimum residual velocity among the proposed hybrid models. Which means that the plate with this orientation has exhibited the maximum energy absorbing characteristics under ballistic impact loading conditions

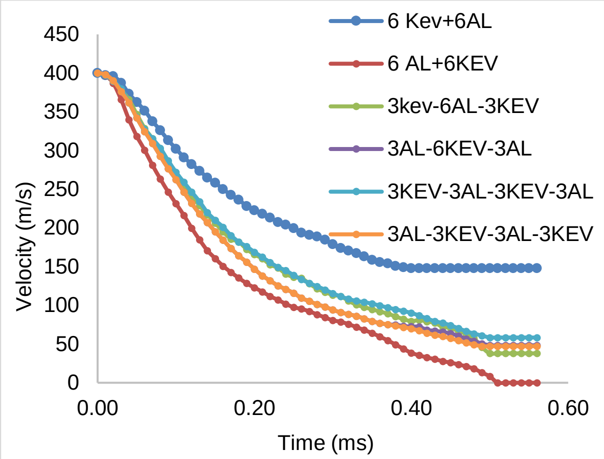
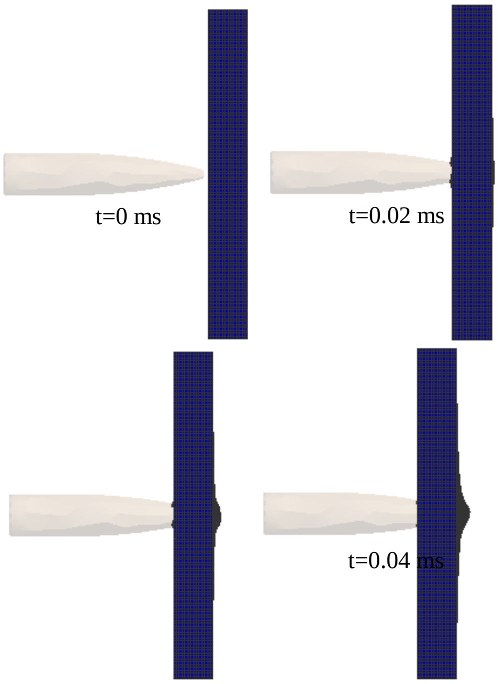


Figure 8. Projectile velocity reduction during ballistic impact for the hybrid targets

Damage propagation on the hybrid model with 6AL-6KEV orientation for ballistic impact loading is given in Figure 9. It is seen that perforation is starting when time equals to the 0.03 ms, and the velocity of the projectile is decreased to zero after 0.55 ms. It is seen that this plate cannot be fully perforated.



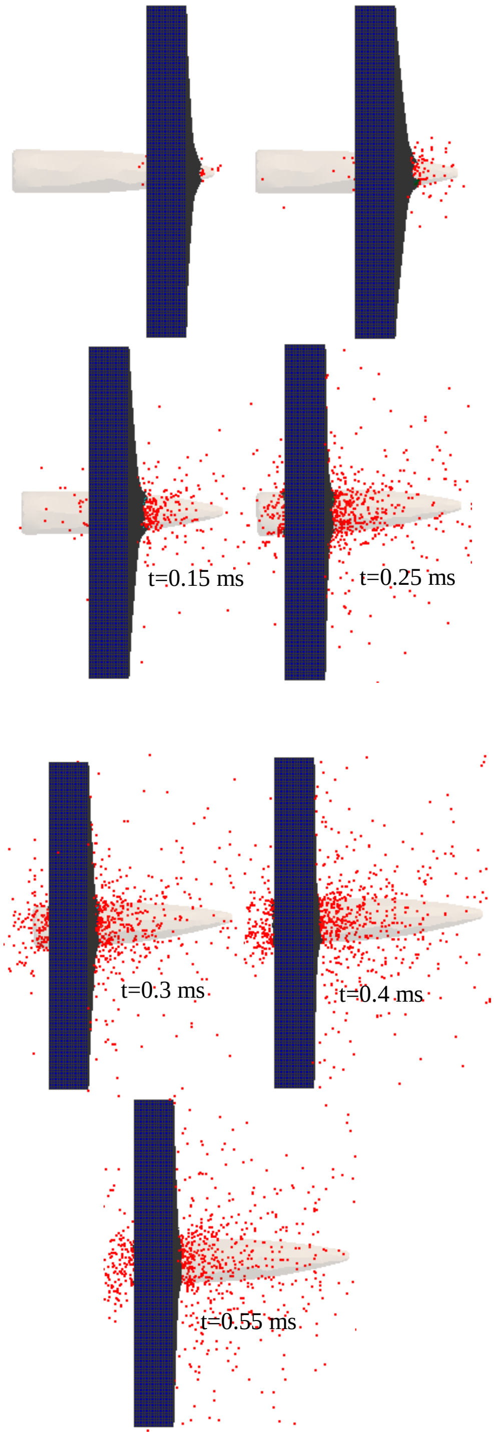
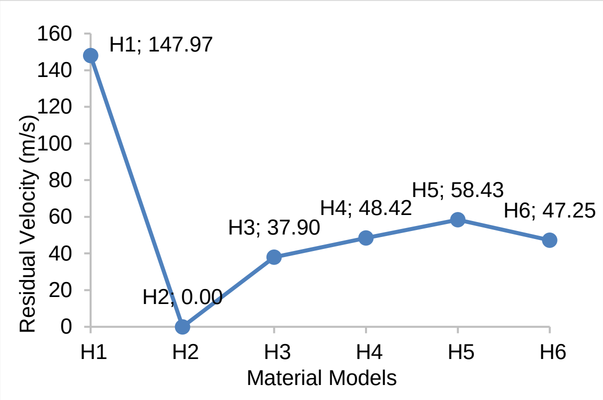


Figure 9. Damage propagation on the 12 mm 6Al+6KEV with ballistic impact loading (Vi=400 m/s)

The residual velocity of hybrid models is given in Figure 10a and Table 5. And the amount of absorbed energy comparison of these models is given in the Figure 10b and Table 5. The Figure and Table show that the residual velocity of the model H1is the highest and it is the smallest (zero) for H2. Difference between H1 and H2 is approximately 148 m/s. The absorbed energy of H2 is approximately 15.85% higher than the absorbed energy of H1.



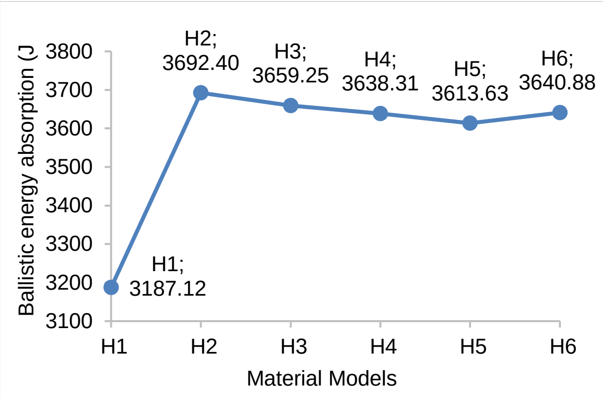


Figure 10. Variation of Residual velocities (a) and Energy absorptions (b) of hybrid models for different thicknesses

Table 5. Residual velocities and Energy absorptions for different material models

Material Models	Residual velocity (m/s)	Ballistic energy absorption (J)
H1	147.97	3187.12
H2	0	3692.40
H3	37.9	3659.25
H4	48.42	3638.31
H5	58.43	3613.63
H6	47.25	3640.88

*$V_{initial}$=400m/s

4. CONCLUSIONS

The ballistic impact resistance of different aluminum alloys, and hybrid models that have different combinations of the 7075 T6 aluminum alloy and Kevlar 29/Epoxy were investigated in this study. The main specific results are;

- The residual velocity of the Al 7075 T6 is the smallest among the used material types. For 5 mm thickness of the target plate, the residual velocity of the Al 7075 T6 is approximately 9.6 % smaller than the residual velocity of the Al 6061 T6. When the thickness is equal to 15 mm, the velocity of projectile decrease to zero the earliest (approximately 20 % earlier than the others) among the used material types.
- Perforation is starting when time equals to the 0.024 ms on the 5 mm target plate with AL 7075 T6 material type, and this plate is fully perforated after 0.2 ms.
- For the target plate with AL7075 T6 material type, amount of the residual velocity is decreased when the thickness of the target plate is increased to 15 mm from 1 mm. When the thickness equal to the 15 mm, the velocity of the projectile is decreased to zero. Which indicates that there is not full perforation of the target at this situation. The residual velocity is decreased 0 m/s from 384.41 m/s and amount of the absorbed energy is increased to 3692.40 J from 282.21 J.
- The target plate which formed having 6AL-6KEV (H1) orientation has the minimum residual velocity among the proposed hybrid models. Which means that the plate with this orientation has exhibited the maximum energy absorbing characteristics under ballistic impact loading conditions.
- For the hybrid model with H1 orientation, perforation is starting when time equals to the 0.03 ms, and the velocity of the projectile is decreased to zero after 0.55 ms.
- The residual velocity of the model H1is the highest and for H2 the smallest (zero). Difference between H1 and H2 is approximately 148 m/s. The absorbed energy of H2 is approximately 15.85 % higher than the absorbed energy of H1.

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