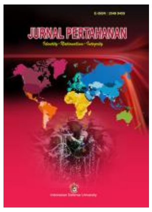
Jurnal Pertahanan

Media Informasi tentang Kajian dan Strategi Pertahanan
yang Mengedepankan *Identity*, *Nationalism* dan *Integrity*
e-ISSN: 2549-9459
http://jurnal.idu.ac.id/index.php/DefenseJournal



A REVIEW OF PENETRATION TUNGSTEN BASED PROJECTILE ON DEPTH OF PENETRATION AT ARMOR OF CERAMIC BASED

Abdul Basyir
Research Center for Physics, Indonesian Institute of Sciences
440 – 442 Building, Puspiptek Area, Muncul, Setu, South Tangerang, Banten, Indonesia 15314
abdu077@lipi.go.id

Erna Shevilia Agustian
Faculty of Defense Technology, Indonesia Defense University
IPSC Area, Sentul, Sukahati, Citeureup, Bogor, West Java, Indonesia 16810
erna_shevilia@yahoo.co.id

Adhistia Amelia
Department of Chemistry, University of York
Heslington, York YO10 5DD, United Kingdom
adhistiaamelia22@gmail.com

Article Info

Article history:
Received 6 August 2020
Revised 1 December 2020
Accepted 1 December 2020

Keywords:
Ceramic-based,
Depth of penetration,
Impact velocity,
Tungsten-based

DOI:
http://dx.doi.org/10.33172/jp.v6i3.890

Abstract

Nowadays, tungsten-based material is used for the core of projectile, while ceramic-based is used for the main material of armor. Tungsten-based material is chosen because it has density and hardness superior to steel based-material. Meanwhile, the ceramic-based can enhance mobility and resistance penetration of armor. Penetration of projectile on target generates an impact velocity parameter. This velocity has resulted when the projectile hits the target. Therefore, the value of impact velocity affects the quantity of depth of penetration (DoP) result. This paper reviews some papers regarding the penetration of tungsten-based projectile on ceramic-based armor. Furthermore, the content of these papers is reviewed by the narrative review method, and the impact velocity and DoP are the main data to analyze. Through this paper, impact velocity has a linear correlation with the DoP, the big of impact velocity produced bigger of DoP, and vice versa. Based on the data in this review, for the same impact velocity, material, and (almost) dimension of a projectile, SiC has better penetration resistance than B4C, TiB2, and Al2O3. Furthermore, the parameter of projectile dimension, projectile material type, target design, and material composition of the target also affects the DoP result.

INTRODUCTION

In the symmetric battlefield, the ability of penetration technology on the projectile is much needed, because the development technology of armor is enhancing rapidly. Initially, the technology of armor was metal-based, but now, this technology is developing to use ceramic-based, ceramic–composite based, and transparent ceramic-based (Grujicic et al., 2012; W. Liu et al., 2016; Yulong & Fan, 1996).

The substitution of metal-based to ceramic-based was caused the ceramic material to have low density with low porosity, where it was enhancing the mobility of personal and/or vehicle that using this armor of ceramic material (Ruys, 2019). Meanwhile, the hardness, toughness, and compressive strength of the ceramic material were better than metal material such as steel, so that ceramic material was to minimize the penetration effect of a projectile (Bracamonte et al., 2016). In Afghanistan and Iraq war, ceramic body armor was used by the United States Army. This body armor could defeat the penetration of small arms from the enemy (National Research Council, 2012). Absolutely, in the armor design, the ceramic material was not stand-alone, but also support by other materials. Furthermore, alumina (Al_2O_3), boron carbide (B_4C), boron silicon carbide (BSiC), silicon nitride, and silicon carbide (SiC) were the ceramic material that often used as an armor material (Holmquist & Johnson, 2005; Saeedi Heydari et al., 2017).

Along with the development of material technology for armor, so the material technology for penetration of projectile must be enhanced. The potential material which could be projectile material was tungsten-based material, such as tungsten heavy alloy, tungsten carbide, tungsten carbide cobalt, and tungsten alloy (Arora & Gopal Rao, 2004). This material had a high density, good strength, and excellent toughness at room temperature and moderately temperatures up to 500 °C (Bhaumik et al., 1992; Chen et al., 2015; Lee et al., 2019).

The depth of penetration (DoP) is the main parameter in observing the penetration ability of projectile, where the impact velocity is one of the parameters affecting the deep of DoP. Moreover, the DoP technique was often used in the research for evaluating the ballistic ability of armor and projectile (Rozenberg & Yeshurun, 1988), and one of the rules was used refer to STANAG 4241.

In terms of ammunition, the main component of ammunition is a primer, propellant, jacket, and projectile. Based on our previous study, impact velocity has a linear correlation with muzzle velocity. The higher muzzle velocity generates higher impact velocity and vice versa, while muzzle velocity has a linear correlation with propellant type and quantity. Generally, for the same propellant quantity, the double base propellant generated higher muzzle velocity than the single base propellant. Besides, for the same propellant type, the bigger quantity of propellant produced higher muzzle velocity than the smaller quantity of propellant (Adliana et al., 2019).

The purpose of the study is to review the effect of tungsten-based projectile penetration on the target of ceramic-based; mainly to observe a correlation between impact velocity and the DoP. Furthermore, since the ballistic impact is a very complex mechanical process, mainly depends on the parameter of the projectile and the density, hardness, toughness, and strength of the target material (Abtew et al., 2019), so that this review will compare some factors, such as dimension, density, hardness, and material type of projectile; design configuration of target; and material composition of target design since those factors affect the result of DoP. This study can also be information for the defense industry in designing a projectile type of armor and can be taken as consideration for military personnel in choosing the projectile and/or armor type.

METHODS

This article uses a narrative review as a type of literature review method. A narrative review was the ‘traditional’ method of reviewing the extant literature and tends to do interpretation on prior knowledge (Sylvester et al., 2013). The method of the review paper had five steps, which involved selecting a review topic, searching and screening the literature, gathering and analyzing the literature, writing the review, and making references (Cronin et al., 2008; Levy & Ellis, 2006; Pare & Kitsiou, 2016). Furthermore, the analysis and synthesis of narrative review often used thematic analysis, content analysis, conceptual framework, and classification criteria (Cronin et al., 2008; Green et al., 2006; Levy & Ellis, 2006). The data in this paper were analyzed with the content analysis method, where the data of impact velocity and DoP were the main data to analyze.

The source information used data of published paper on the sciencedirect.com website (Elsevier) and the keyword for searching this paper was "penetration of tungsten on ceramic". This review involved 20 papers with a range of year published papers from 1995 to 2020. Specifically, the main observation was a relation between impact velocity and depth of penetration for projectile material of tungsten, tungsten carbide, tungsten carbide-cobalt, and tungsten heavy alloy; and for target material of alumina, silicon carbide, boron carbide, and titanium diboride. The content of these papers is reviewed, and all related data were compiled in table and chart form. Therefore, the scatter chart type of Microsoft Excel was used in this review to determine correlation and regression between impact velocity and depth of penetration. Afterward, the result of each target chart was analyzed by qualitative and semi-quantitative analysis. Moreover, this study did not only discuss the relation between impact velocity on the DoP, but also the effect of the other parameters (projectile and target) on the DoP result. Furthermore, the 5 (five) types of the ceramic target were determined the potential ceramic type as armor material with better penetration resistance. Meanwhile, all data of tungsten-based projectile penetration on the target of ceramic-based in this review were based on experimental results.

RESULT AND DISCUSSION

The result of ballistic performance was different for each material type of the target. One parameter used to see this performance was the relation between impact velocity and depth of penetration (DoP). In the different target materials such as ceramic-based boron carbide, silicon carbide, alumina, and titanium diboride, the same impact velocity resulted in differences in the DoP. This was caused by some other parameters of projectile and target, such as dimension-geometry and material type of projectile, design configuration of a target, and material composition of the target design.

The Target Material of Boron Carbide (B_4C)

In a previous study, boron carbide had higher ballistic efficiency than both silicon carbide and alumina, for the penetration by the projectile of caliber 0.30 AP M2 (Moynihan et al., 2000). However, other research stated that for the same thickness of target, boron carbide performed worse than silicon carbide and titanium boride (Robertson & Hazell, 2003). For this target, the type is reviewed relation between the impact velocity and DoP by tungsten alloy, tungsten heavy alloy, and tungsten carbide-cobalt projectile, where the total data was used in this analysis about 17 data. Meanwhile, the boron carbide in this review had different density and hardness properties.

Tungsten heavy alloy projectile was used in the first and second experiment, where the length of the projectile in the first experiment was bigger than in the second experiment. The main target of these two experiments was composed of boron carbide with almost the same density, but the main target in the first experiment was covered a SS2541-3 material with a thickness of 1, 2, and 4 mm, while the main target in the second experiment had not to cover material. Furthermore, the first experiment did not have a backing target, while the second experiment consisted of HH-RHA steel with a hardness of 4.5 GPa as backing target (Westerling, Lundberg, & Lundberg, 2001; Rosenberg, Dekel, Hohler, Stilp, & Weber, 1997).

For the third attempt, a tungsten alloy projectile was applied with a length of 25.4 mm and a diameter of 6.35 mm. Moreover, this projectile had a density bigger than the projectile in the first and second experiments. Meanwhile, the main target of this experiment did not have cover material, but this main material was supported by 4340 steel as a backing target with the hardness of 3.8 GPa. Moreover, the thickness of the main target was composed of 10.4, 15.2, 19.3, and 28.0 mm (Reaugh et al., 1999).

The fourth research used tungsten carbide-cobalt projectile from ammunition of 7.62 × 51 mm FFV caliber. Moreover, the design of the target was composed of the main target and backing target. The material of the main and backing target was arranged of boron carbide and aluminum alloy (6082-T651 type). The thickness of the main and backing target was 6.5 mm and 75 mm. Meanwhile, the backing target in this research had the smallest hardness, about 0.9 GPa (Robertson & Hazell, 2003). The detailed data of the impact velocity and DoP from these experiments can be seen in Figure 1 and Table 1.

The range of impact velocity was used about 973 – 2601 m/s, while the depth of penetration was produced at around 3.8–37.1 mm. From figure 1, generally, impact velocity shows a linear correlation in the depth of penetration result.

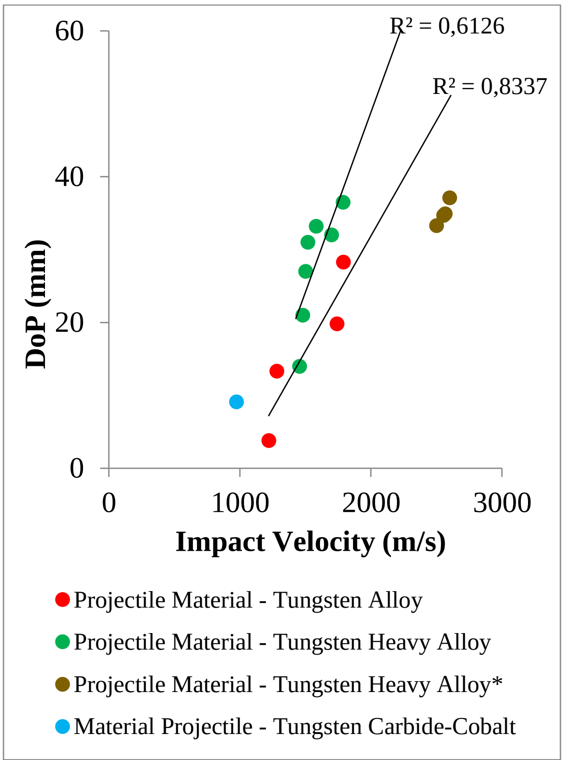


Figure 1. The chart of impact velocity versus DoP was produced of tungsten alloy (red dots), tungsten heavy alloy (green and brown dots), and tungsten carbide-cobalt (blue dots) projectile penetration on the main target (B_4C)

Source: Processed by Authors, 2020

Furthermore, from this data, it can be observed that the dimension of projectile gave an effect on deeper of DoP, the projectile with bigger dimension generated deeper DoP on target and vice versa. It can be seen at the DoP result by penetration of projectile with the length of 150 mm and length of 72.5 mm. For almost similar impact velocity (around 1700 m/s), the projectile with the length of 150 mm produced DoP of 36.5 mm, while the projectile with the length of 72.5 mm generates DoP of 32.0 mm. Even though the main target of the projectile with a bigger dimension consisted of cover material, while the main target of the projectile with a smaller dimension was not covered by material. Unfortunately, in generating the same impact velocity, the projectile with a bigger dimension requires more propellant quantity than the projectile with a smaller dimension. Since the dimension of projectile could affect the impact velocity quantity, where for the same quantity and type of propellant, the projectile with bigger dimension generated smaller impact velocity than the projectile with smaller dimension (Basyir et al., 2019a).

Moreover, the configuration of the target has brought an effect to reduce the penetration of projectile, where for almost the same impact velocity and the same projectile dimension, the penetration of projectile on the main target with cover material generated smaller DoP than penetration on the main target without the front target. Meanwhile, Westerling et al. found that the cover material of the main target had a small influence on the DoP result, especially in the high impact velocity (Westerling et al., 2001). Furthermore, the thickness of the front target has influenced to reduce the penetration of projectile; a thicker front target can generate smaller DoP than the thinner front target. It can be seen at DoP in the main target with a front target of 4 mm and 2 mm, where the front target of 2 mm was found DoP at 27 mm, while in the front target of 4 mm was obtained DoP at 21 mm.

From these data, the hardness of boron carbide cannot significantly reduce the projectile penetration on this material, where the highest DoP result is found at the boron carbide with high hardness. Although, it depends on the projectile dimension used in the penetration process. Probably, if the dimension of the projectile is the same, the main target with high hardness will result in smaller DoP than on the main target with low hardness. Therefore, the dimension of the projectile has an important role to generate bigger DoP.

From this review in this section, on the whole, the dimension of the projectile, configuration of the target, and thickness of the front target have an important role to generate the bigger DoP, where the projectile with bigger dimension and the thin front target can generate the bigger DoP. Moreover, the configuration target with the front target, the main target, and the backing target can generate a smaller DoP than the target configuration without cover material and backing target.

The Target Material of Silicon Carbide (SiC)

The total data used in this analysis was about 56 data. These data were obtained from 5 (five) articles regarding penetration by the tungsten-based projectile on silicon carbide. The articles were published in 1997, 2000, 2005, 2008, 2016, and 2020. The impact velocity used was 380 m/s until 3445 m/s and generated a depth of penetration of about 0.8 – 62.4 mm.

The material projectile in this experiment was tungsten heavy alloy and tungsten. This projectile was shot to the main target, silicon carbide, and the design of the target was composed of the front, main, and backing target. The first and second experiments used the tungsten alloy projectile with a length of 80 mm and a diameter of 2 mm. However, the material of the front target at the two experiments is different, where the first experiment used OFHC copper material with a thickness of 8 mm, while the second experiment used steel (SIS 2541-3 type) with a thickness of 8 mm. Furthermore, the main target in the first experiment used four types of SiC (SiC-B, SiC-HPN, SiC-N, and SiC-SC1RN) with different hardness (25.2, 25.3, 27.2, and 28.9 GPa), but the same thickness. The main target for the second experiment was two types of SiC (SiC-PAD Method and SiC-HIP Method), whilst the hardness of this experiment was smaller than the first experiment. In the back of the main target for the first and second experiment was arranged of steel (Maraging 350 type) and RHA steel, but the Maraging 350 steel had smaller hardness than RHA steel (Lundberg & Lundberg, 2005; Lundberg, Renström, & Lundberg, 2000).

The third and fourth experiment was also using tungsten heavy alloy projectile, but the length of the 2 (two) experiments was different from the first and second experiment, whereas the length of the third and fourth experiment was 90 mm and 40 mm, with a diameter of 6 mm and 16 mm. Moreover, the cover material of the third experiment consisted of copper and without copper material, while the cover material in the fourth experiment was composed of aluminum alloy, mild steel, copper alloy, and no (without front target) material. The main target in these two experiments was three types of SiC, so that hardness and density at these three types of the main target were slightly different. Furthermore, the backing material for these two experiments was the steel of RHA type with different thicknesses (Behner, Heine, & Wickert, 2016; Luo et al., 2020).

Meanwhile, for the fifth and sixth attempts, tungsten material was used as a projectile. The cover and backing target were composed of aluminum (6061-T6 type) with a hardness of 1.1 GPa, and the thickness of the cover and the backing target was about 3.75 and 15.24 mm, respectively. The main material for the fifth and sixth attempts was SiC with a density of 3220 kg/m^3 and 3090 kg/m^3, while the thickness of SiC in the two attempts was 48.26 and 26 mm, respectively (Cao et al., 2008; Orphal & Franzen, 1997). The data shows that SiC material in the fifth attempt is denser than in the sixth attempt. The detailed information regarding impact velocity and DoP of this penetration can be seen in Figure 2 and Table 2.

According to Figure 2, the penetration of tungsten heavy alloy on SiC produces a linear relationship between impact velocity and DoP, but penetration of this projectile generates two trends of the relationship between impact velocity and DoP. The two trends have a similar form, linear relation, but in a different direction. The first trend was produced by impact velocity of 1200 m/s until 1500 m/s, while the second trend was generated by impact velocity below 1200 m/s and upper than 1500 m/s. It is interesting because the first trend is produced from some experiments with different target configurations and different material types of front target, but it results in the same trend. The same trend occurs in the second experiment, where this trend is generated from experiments with different target configurations and different material types in this configuration. Hence, it needs deep research to elaborate on this phenomenon, especially for small scope of impact velocity (such as in the range of 1401 m/s - 1490 m/s) but on different target configurations.

The data shows the material type of front and the backing target has affected to reduce DoP on the main target; generally, the front and backing target with high hardness can reduce penetration effect of a projectile on the main target, such as penetration of projectile with length of 80 mm and diameter of 2 mm on two types of configuration target, (1) main target with SIS 2541-3 (hardness of 3.2 GPa) as cover material and backing target, and (2) main target with OFHC copper as cover material (hardness of below 1 GPa) and steel (Maraging 350 type) as backing target. For almost similar impact velocity numbers, the first configuration can protect the main target better than the second configuration, so DoP on the main target in the first configuration is smaller than the second configuration. Even though the main target (SiC) in the first configuration had smaller hardness than SiC in the second configuration. Moreover, if the hardness of the cover plate is too small, so this cover can't give significant protection to the main target (Goh et al., 2017).

Meanwhile, in the other case, the aluminum alloy with lower hardness than copper alloy and mild steel can protect the

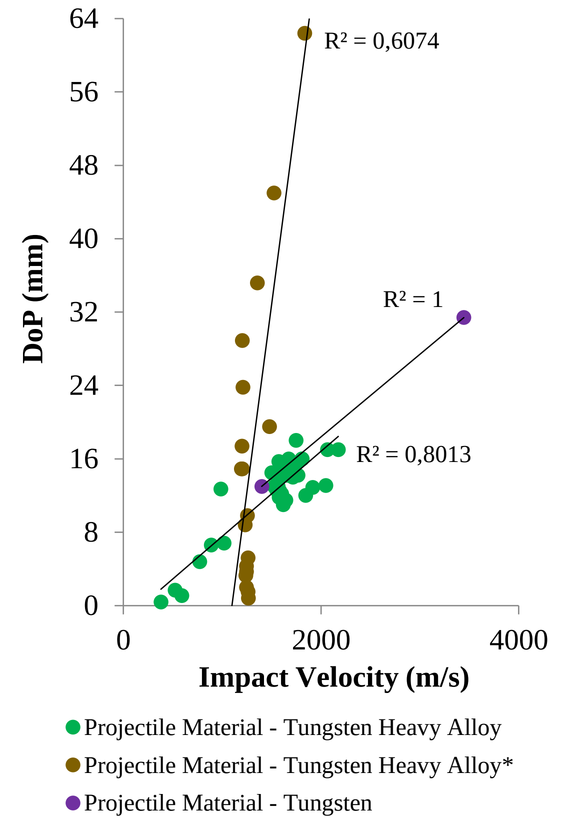


Figure 2. The chart of impact velocity versus DoP was generated of tungsten heavy alloy (green and brown dots) and tungsten (purple dots) projectile penetration on the main target (SiC)

Source: Processed by Authors, 2020

main target better than copper alloy and mild steel. It was caused by aluminum alloy had a small elastic impedance, where the small elastic impedance can generate a big reflected wave when penetration between projectile and target occurred. This big reflected wave can reduce DoP on the main target (Luo et al., 2020).

It seems similar when B_4C is used as the main target, in the main target of SiC, the projectile with a bigger dimension generates bigger DoP compared to the projectile with a small dimension, even though the material of the main target (SiC) for a bigger dimension of the projectile was support by backing target with the highest hardness of all research in this review. It can be seen at the DoP result from penetration by (1) projectile with length of 90 mm and diameter of 6 mm, and (2) projectile with length of 80 mm and diameter of 2 mm; for almost the same impact velocity (around of 1660 m/s), the projectile (1) generated DoP 15.9 of mm, while the projectile (2) produced DoP of 14.2 mm. The front target of these two main targets was copper material.

For the same dimension of a projectile, the density of the main target (SiC) had also an effect to reduce the penetration of the projectile, the SiC with a density of 3090 kg/m^3 had smaller penetration resistance than SiC with a density of 3220 kg/m^3. Although, the impact velocity on SiC with a density of 3220 kg/m^3 was bigger than on SiC with a density of 3090 kg/m^3. It is caused by the minimize pore in the material with the higher density, so this material is more difficult to crack when penetrating.

Briefly, from the review in this section, the parameters such as target configuration, the dimension of the projectile, the density of the main target have influenced to generate bigger DoP on the main target. The projectile with a bigger dimension can produce a bigger DoP on the target. Moreover, the target with configuration consists of a cover, main, and backing target can improve performance ballistic of the target. Furthermore, the main target in this configuration can reduce the penetration of projectile, if this main target has a higher density, more than 3220 kg/m^3.

The Target Material of Alumina (Al_2O_3)

There was 6 (six) research analyzed in this section, which was published in the year of 1995, 2010, 2013, 2016, and 2019. Around 69 data of impact velocity and DoP were reviewed from these researches. The first and second experiments used tungsten heavy alloy projectile. In the first experiment, for impact velocities of around 1200 m/s and 1700 m/s used projectile with a length of 72.5 mm and diameter of 5.8 mm, whilst for impact velocity of around 2500 m/s and 3000 m/s used projectile with a length of 49.5 mm and diameter of 5 mm. Furthermore, the main target of this experiment used alumina with a density of 3800 kg/m^3 and hardness of 21 GPa. Meanwhile, the main target had rubber foil as cover material, and steel (HH-RHA type) as a backing target, where the thickness of this front and backing target was 1.5 mm and 60 mm. Moreover, the thickness of this main target was varied from 10 mm to 101.2 mm (Hohler et al., 1995).

The second attempt used alumina with a thickness of 90 mm as the main target. The density of this main target was bigger than the density of the main target in the first experiment, but this main target had a smaller hardness than the main target in the first experiment. Furthermore, the main target in this research did not have cover material but used a backing target of steel (603 armor type) with a thickness of 80 mm. Then, the projectile in this attempt had a length of 120 mm and a diameter of 5.6 mm (Jinzhu et al., 2017).

Moreover, the third and fourth research used tungsten alloy projectile with different dimensions. The projectile in the third research was longer than the projectile in the fourth research, where the length of the third and fourth experiments was 45 mm and 29 mm. The main target of the third experiment had cover material without backing target, whilst the main target in the fourth experiment used front and backing target. Furthermore, the main target in the third experiment was alumina (AD-90 type) with a density of 3625 kg/m^3 and thickness of 29.9 mm. This main target was supported by the front target of steel with a thickness of around 10.2 mm. In the fourth experiment, the main target was AD-95 alumina type with a density of 3600 kg/m^3 and thickness of 11 mm. In front and backing of the main target consisted of 4340 steel materials with a thickness of 5 mm and 8 mm, respectively (Ning, Ren, Guo, & Li, 2013; Tan, Han, Zhang, & Luo, 2010).

For the fifth attempt applied projectile from tungsten carbide material, where the dimension of this projectile referred to the projectile dimension of 7.62 mm Armor Piercing 8 ammunition. Moreover, the main target in this attempt was alumina with a thickness of 8 mm, and this main target was supported by a backing target of polycarbonates, without a front target (Carton, Johnsen, Rahbek, Broos, & Snippe, 2019).

Meanwhile, a projectile of tungsten carbide cobalt (WC-8Co) with dimension referred to as ammunition of SS109 5.56 × 45 mm caliber was used in the sixth research. This projectile had a density of 14800 kg/m^3 and a hardness of 16.43 GPa. Moreover, the main target was alumina with a density of 3940 kg/m^3 and hardness of 14.7 mm. This thick main target of 10 mm was supported by a backing target of plasticine with a thickness of about 150 mm (Basyir, Bura, & Lesmana, 2019b). The detailed information about the impact velocity and DoP of this review can be seen in Figure 3 and Table 3.

The range of impact velocity was used in this review between 818 and 3037 m/s, and this impact velocity resulted in DoP about 2.9 until 68.0 mm. Figure 3 shows a chart of the relationship between impact velocity and DoP on target material (alumina) by penetration of tungsten alloy, tungsten heavy alloy, tungsten carbide, and tungsten carbide cobalt projectile. Generally, this chart describes a linear correlation between impact velocity and DoP. From this figure, for almost the same impact velocity, tungsten carbide-cobalt projectile generated DoP bigger than tungsten carbide, tungsten heavy alloy, and tungsten alloy projectile. Even though, the dimension of tungsten carbide-cobalt projectile had the smallest in this review. It was caused by the existence of Co binder, and where this binder enhanced flexural strength and fracture toughness on the matrix of tungsten carbide material (K. Liu et al., 2018). Therefore, the physical and mechanical properties of material must be considered in choosing the material as core projectile.

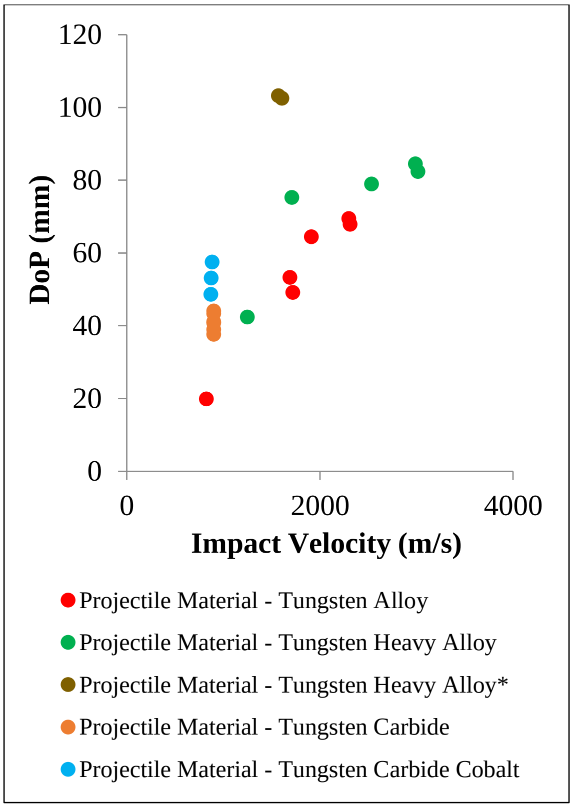


Figure 3. The chart of impact velocity versus DoP was generated of tungsten alloy (red dots), tungsten heavy alloy (green and brown dots), tungsten carbide (orange dots), and tungsten carbide - cobalt (blue dots) projectile penetration on the main target (Al_2O_3)

Source: Processed by Authors, 2020

Furthermore, the target configuration of this penetration by tungsten carbide-cobalt projectile did not have cover material and was only supported by the very lower hardness material. It shows that the configuration of the target had an important role to reduce the penetration of superior projectile. In detail, it can be seen in Figures 4 and 5. From the two figures, there was a significant difference in total penetration results from the main target with the front target and without the front target. At the main target without the front target, the impact velocity of around 1500 m/s produced total penetration of about 100 mm, whilst at the main target with cover material, the impact velocity of 3000 m/s generated total penetration of around 83 mm. It is similar to a study by Anderson et al, the cover plate of steel with different hardness had a relation with ballistic performance; the cover plate with high hardness was able to protect the main target (ceramic) better than the cover plate with low hardness (Anderson & Royal-Timmons, 1997). Moreover, the total penetration on the main target increased considerably, if the projectile in this penetration had a bigger dimension.

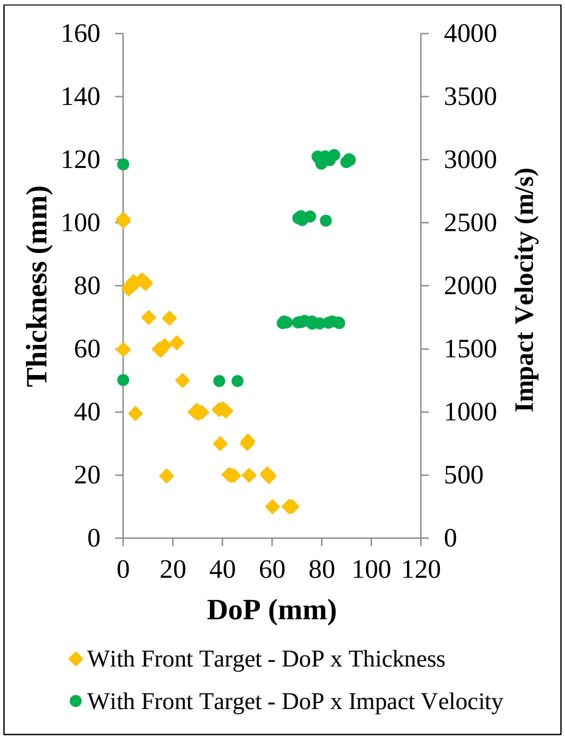


Figure 4. The chart of DoP versus thickness (Main Target) and DoP versus impact velocity were produced of tungsten heavy alloy projectile penetration on the main target (Al_2O_3) with cover material (rubber foil)

Source: Processed by Authors, 2020

From figure 4, if the impact velocity did not have a significant difference in which the impact velocity was only different less than 100 between one and the other, so for almost the same projectile dimension and almost the same target configuration, this impact velocity could not generate DoP with significant differences. However, from this data, there was a limitation of projectile penetration, where projectile with length of 72.5 mm and diameter of

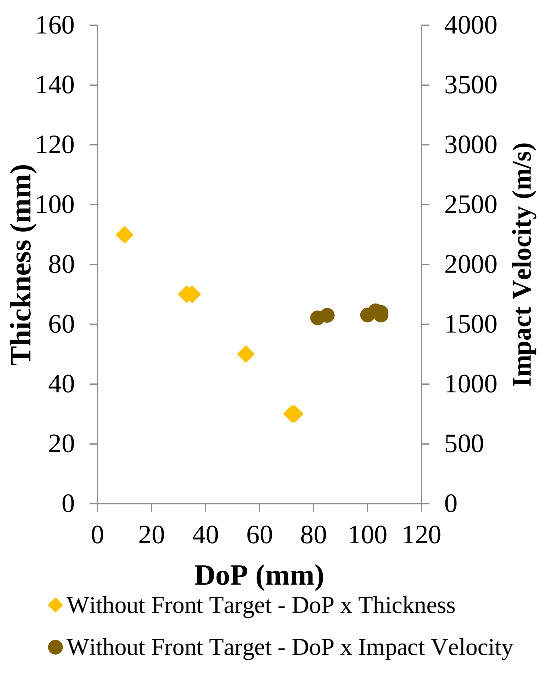


Figure 5. The chart of DoP versus thickness (Main Target) and DoP versus impact velocity were produced of tungsten heavy alloy projectile penetration on the main target (Al_2O_3) without cover material (rubber foil)

Source: Processed by Authors, 2020

5.8 mm did not perforate on the main target with a density of 3800 kg/m^3, the hardness of 21 GPa, and thickness of 59.8 mm. Other than that, this main target had a cover material of rubber foil with a thickness of 1.5 mm and was supported by a backing target of HH-RHA with a hardness of 4.4 GPa. When the thickness of this main target was increased to 100 mm, the tungsten heavy alloy projectile (length of 49.5 mm and diameter of 5 mm) with an impact velocity of around 3000 m/s could not also perforate on this target configuration.

Overall, from this review, the dimension and material type of projectile, and target configuration without a front target are the main parameters to generate bigger DoP, while the target configuration with front and backing target and less dimension of the projectile are the main parameters to produce superior of ballistic performance.

The Target Material of Titanium Diboride (TiB_2)

There were 4 (four) experiments reviewed for the target material (titanium diboride), where the material of projectile in the four experiments was tungsten and tungsten heavy alloy material. This review involved 16 data from an experiment in 1994, 1997, 1999, and 2000. Furthermore, the range of impact velocity was used about 1310–2630 m/s, while from this range generated DoP of 2.0–38.0 mm.

The tungsten alloy projectile was used in the first and second attempts. Moreover, the diameter of a projectile in the first experiment was bigger than in the second experiment. Meanwhile, the target configuration for these two experiments consisted of the main target and backing target, without the front target. The main target for the first experiment was bigger than for the second experiment. Furthermore, the backing target for the first and second experiment consisted of aluminum alloy (2024 T351 type) and 4340 steel, respectively (Woodward et al., 1994; Reaugh et al., 1999).

Next, the tungsten heavy alloy projectile was used in the third and fourth attempts. The length of the projectile in the third attempt was longer than in the fourth attempt. Furthermore, these two researches used target configuration without cover material. The density of the main target for the third research was slightly bigger than for the fourth research. Moreover, the fourth research was only used the main target, while the third research did not only used the main target, but it also used hard steel material as a backing target (Rosenberg et al., 1997; Lundberg et al., 2000). Furthermore, the detailed data regarding impact velocity and DoP for this review can be seen in Figure 6 and Table 7.

The impact velocity was used in this review between 1209–2630 m/s, and this velocity generated a DoP result of 2 – 38.0 mm. Figure 6 shows the linear relation between impact velocity and DoP. The bigger impact velocity generates the bigger DoP, and vice versa.

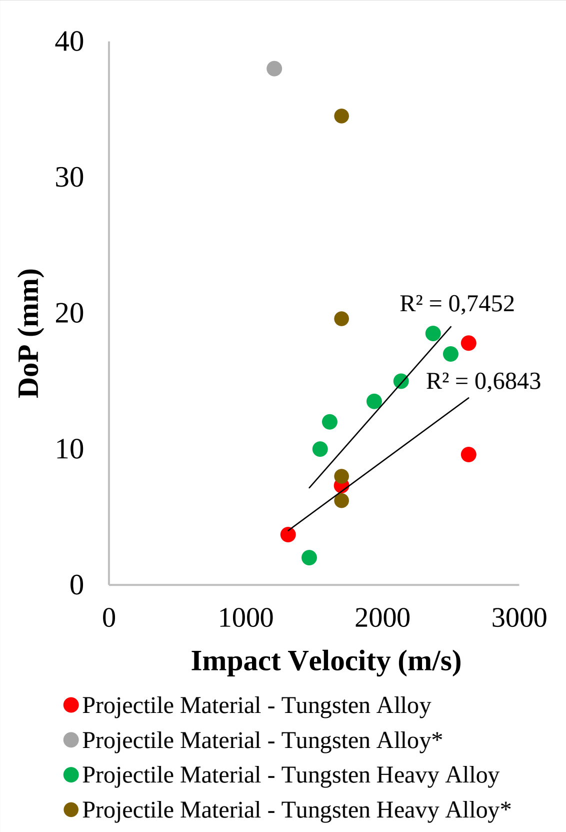


Figure 6. The chart of impact velocity versus DoP was generated of tungsten alloy (red and grey dots) and tungsten heavy alloy (green and brown dots) projectile penetration on the main target material (TiB_2)

Source: Processed by Authors, 2020

Furthermore, based on this data, the projectile with a bigger dimension produced a bigger DoP on the target and vice versa. It can be seen at penetration by a projectile in fourth research with a length of 80 mm, where this length of the projectile was the longest projectile. For almost the same impact velocity (around 1650 m/s), this projectile generated DoP of 32 mm on the main target without front and backing target, while the projectile with a length of 25.4 mm in the second experiment produced DoP of 22.2 mm, even though this main target of this experiment was supported by 4340 steel as backing target.

Moreover, the longest projectile in this review with a diameter of 2.0 mm (in the fourth experiment) had a smaller penetration performance than the projectile with a length of 72.5 mm and diameter of 5.8 mm (in the third experiment). It can be understood because the projectile area in the third experiment was bigger than the projectile in the fourth experiment. Even though the main target in the third experiment was supported by the backing target of hard steel, the projectile in this experiment produced DoP bigger than the projectile in the fourth experiment.

For almost the same impact velocity and diameter of projectile, the material type of backing target affected to increase the ballistic performance of the main target, where the DoP in the first experiment was bigger than in the second experiment. Moreover, the backing target of the main target was aluminum alloy (in the first experiment), while the backing target in the second experiment was 4340 steel. The hardness of 4340 steel was bigger than aluminum alloy so that the 4340 steel could minimize penetration of projectile better than the aluminum alloy. Since the hardness parameter reduced penetration performance of projectile (Basyir et al., 2019b). Although the main target in the first experiment was titanium diboride with the highest density and hardness, these properties could not minimize penetration of the projectile.

The thickness of the main target could not reduce total DoP significantly. It can be seen at projectile penetration with an impact velocity of 1700 m/s and 2630 m/s. The total DoP on the thin main target was not significantly different from in the thick main target.

Generally, from the review of penetration projectile on the main target of titanium diboride, same with the previous section, the parameter of the dimension of projectile and configuration of the target has an important role to generate bigger DoP. The projectile with a bigger volume (length and radius) can generate a bigger penetration performance. Meanwhile, the main target consists of the front and the backing target can produce smaller penetration of projectile, compared to the main target without front and backing target.

Effect of Ceramic Type

Figure 5 shows that from the four types of the main target, such as boron carbide, silicon carbide, alumina, and titanium diboride, with almost the same impact velocity (~1700 m/s) and projectile dimension (length of 72.5 and/or 80 mm and diameter of 5.8 and/or 2 mm), the SiC was the best penetration resistance, where the total DoP of SiC and B_4C for this comparison was 43.0 and 71.6 mm, respectively. Although in this comparison, the design target of SiC had a front target (SIS 2541-3 type), while the B4C did not have a front target. But in the other research, the penetration of projectile with an impact velocity of 1581 m/s and length of 150 mm generated a total DoP of 72.8 mm in the main target of B_4C, even though the B_4C in this experiment had steel (SIS 2541-3 type) as cover material.

Therefore, although from the mechanical properties data, B_4C had properties (hardness, compressive strength, Young modulus, and yield strength) bigger than SiC (Lundberg et al., 2000; Rosenberg et al., 1997). So, the SiC is possibly to have better penetration resistance than B_4C since this material had superior in bending strength and fracture toughness (increasing of density), compared to B_4C.

Moreover, from almost the same impact velocity and dimension of a projectile, the boron carbide had the best penetration resistance than TiB_2 and Al_2O_3 (see Figure 5). It was because bending strength, yield strength, and hardness of B_4C were superior if compared to TiB_2 and Al_2O_3. Furthermore, TiB_2 and Al_2O_3 had much bigger density than B_4C, where the increase of density enhanced fracture toughness but decreased on Young's modulus and hardness (Cui et al., 2017).

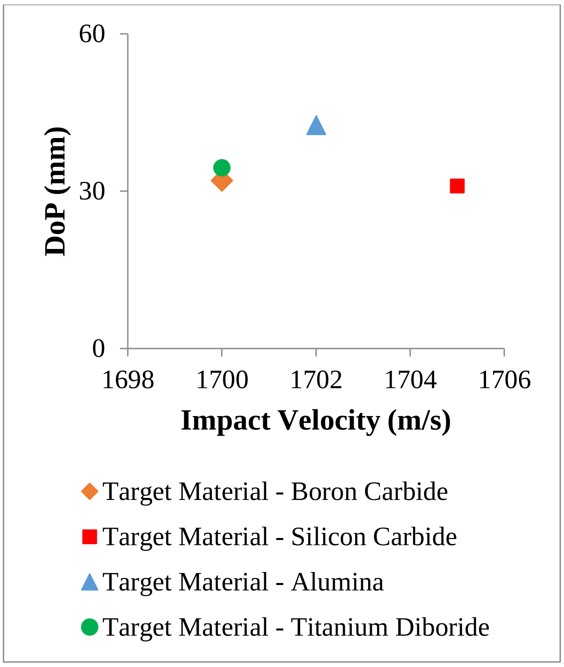


Figure 7. The chart of impact velocity versus depth of penetration was generated by tungsten alloy projectile on target, boron carbide, silicon carbide, alumina, and titanium diboride

Source: Processed by Authors, 2020

Based on the US National Institute of Justice (NIJ), the body armor consisted of 5 (five) classifications, level of IIa, II, IIIa, III, and IV, where this body armor in each level had a thickness of 4 mm, 5 mm, 6 mm, 15 mm, and 20 mm, respectively (National Institute of Justice, 2014). Refer to this standard, the maximum thickness of body armor was 20 mm. From this review, to perforate the main target of B_4C with a thickness of 20 mm was required the projectile with a length of 25.4 mm, a diameter of 6.35 mm, a density of 18360 kg/m^3, the hardness of 31 GPa, and impact velocity of 1700 m/s. Furthermore, the target configuration for this setting is without the front target. Meanwhile, for the main target of SiC, to perforate this material was required projectile with a thickness of 20 mm was needed projectile with a length of 80 mm, a diameter of 2 mm, a density of 17600 kg/m^3, and impact velocity of 1805 m/s. Besides, the target configuration for this scheme was the main target with cover material (SIS 2541-3 steel type).

Moreover, to perforate the main target of alumina with a thickness of 20 mm was requisite projectile with a length of 49.5 mm, a diameter of 5 mm, a density of 17600 kg/m^3, the hardness of 5.35 GPa, and impact velocity of 1700 m/s. The main target of this experiment has cover material (rubber foil), whereas for the main target of titanium diboride, to perforate this material was needed the projectile with a length of 80 mm, a diameter of 2 mm, a density of 17600 kg/m^3, and impact velocity of 1465 m/s. The target configuration of this attempt also involved steel (SIS 2541-3 type) as a front target.

CONCLUSIONS, RECOMMENDATION, AND LIMITATION

From this review, this study found that impact velocity had a linear correlation with the depth of penetration (DoP). The big impact velocity by projectile generated bigger of DoP on target and vice versa. However, if the gap of impact velocity between one and the other was small, for example, the gap was less than 100, so that the DoP result did not show a significant difference.

Furthermore, for almost the same impact velocity, the same material, and the dimension of projectile, target configuration, the SiC material had better penetration resistance than B_4C, TiB_2, and Al_2O_3. Besides, for almost similar projectile dimensions, the same material of projectile and target configuration, the minimum impact velocity to perforate the B_4C, SiC, Al_2O_3, and TiB_2 with a thickness of 20 mm was around 1500 m/s.

Furthermore, the other parameters also affected DoP result:

a) The dimension of the projectile. The big dimension of the projectile generated the big DoP and vice versa.
b) Material type of projectile. The superior physical (density) and mechanical properties (high hardness, high flexural strength, high fracture toughness, etc.) on projectile produced the deeper of DoP and vice versa.
c) Design of target. The main target with cover material has higher penetration resistance than the main target without a front target, and the front target with low elastic impedance could minimize DoP better than the front target with high elastic impedance.
d) The material composition of the target design. The front/main/backing target consists of superior material in the physical and mechanical property had higher penetration resistance than front/main/backing target arranged of inferior material in physical and mechanical property.

However, some limitations are worth noting. Although the hypotheses in this research were supported by simple statistics through the chart of linear regression, the experiment design of the 4 (four) types of ceramic in this review was not quite the same. Therefore, for future work, it should be arranged the same experiment design of the ballistic test, on the projectile, shooting distance, and target. Besides, the next research should develop various settings with a large and/or small number of different impact velocities on the main target, with and/or without cover material.

REFERENCES

Abtew, M. A., Boussu, F., Bruniaux, P., Loghin, C., & Cristian, I. (2019). Ballistic impact mechanisms – A review on textiles and fibre-reinforced composites impact responses. *Composite Structures*, *223* (November 2018), 110966. https://doi.org/10.1016/j.compstruct.2019.110966

Adliana, N., Bura, R. O., & Ruyat, Y. (2019). Analisis pengaruh karakteristik propelan terhadap balistik interior pada munisi kaliber kecil. *Teknologi Persenjataan*, *1*(1), 39–62.

Anderson, C. E., & Royal-Timmons, S. A. (1997). Ballistic performance of confined 99.5%-Al2O3 ceramic tiles. *International Journal of Impact Engineering*, *19*(8), 703–713. https://doi.org/10.1016/s0734-743x(97)00006-7

Arora, A., & Gopal Rao, V. G. (2004). Tungsten heavy alloy for defence applications. *Materials Technology*, *19*(4), 210–216. https://doi.org/10.1080/10667857.2004.11753087

Basyir, A., Bura, R. O., & Lesmana, D. (2019a). Analisis Pengaruh Densitas dari Inti Proyektil Baja dan Tungsten Carbide-CObalt (WC-8Co) terhadap Penetrasi Proyektil pada Target Silicon Carbide (SiC). *Teknologi Persenjataan*, *1*(2), 133–150.

Basyir, A., Bura, R. O., & Lesmana, D. (2019b). Experimental Consideration of Projectile Density and Hardness Effect on Its Penetration Ability in Alumina Target. *Journal of Defense Acquisition and Technology*, *1*(1), 9–15. https://doi.org/10.33530/jdaat.2019.1.1.9

Behner, T., Heine, A., & Wickert, M. (2016). Dwell and penetration of tungsten heavy alloy long-rod penetrators impacting unconfined finite-thickness silicon carbide ceramic targets. *International Journal of Impact Engineering*, *95*, 54–60. https://doi.org/10.1016/j.ijimpeng.2016.04.008

Bhaumik, S. K., Balasubramaniam, R., Upadhyaya, G. S., & Vaidya, M. L. (1992). Oxidation behaviour of hard and binder phase modified WC-10Co cemented carbides. *Journal of Materials Science Letters*, *11*(21), 1457–1459. https://doi.org/10.1007/BF00729663

Bracamonte, L., Loutfy, R., Yilmazcoban, I. K., & Rajan, S. D. (2016). Design, manufacture, and analysis of ceramic-composite armor. In *Lightweight Ballistic Composites: Military and Law-Enforcement Applications* (pp. 349–367). Elsevier Ltd. https://doi.org/10.1016/B978-0-08-100406-7.00012-X

Cao, L. Z., Liu, G. X., Yan, D. M., Duan, G. W., & Chang, Y. W. (2008). Research on fabricating technology of high protection coefficient silicon carbide ceramic armor. *Ordnance Material Science Engineering*, *5*, 43–46.

Carton, E. P., Johnsen, B. B., Rahbek, D. B., Broos, H., & Snippe, A. (2019). Round robin using the depth of penetration test method on an armour grade alumina. *Defence Technology*, *15*(6), 829–836. https://doi.org/10.1016/j.dt.2019.07.014

Chen, L., Yi, D., Wang, B., Liu, H., Wu, C., Huang, X., Li, H., & Gao, Y. (2015). The selective oxidation behaviour of WC-Co cemented carbides during the early oxidation stage. *Corrosion Science*, *94*, 1–5. https://doi.org/10.1016/j.corsci.2015.02.033

Cronin, P., Ryan, F., & Coughlan, M. (2008). Undertaking a literature review: a step-by-step approach. *British Journal of Nursing (Mark Allen Publishing)*, *17*(1), 38–43. https://doi.org/10.12968/bjon.2008.17.1.28059

Cui, F., Wu, G., Ma, T., & Li, W. (2017). Effect of ceramic properties and depth-of-penetration test parameters on the ballistic performance of armour ceramics. *Defence Science Journal*, *67*(3), 260–268. https://doi.org/10.14429/dsj.67.10664

Goh, W. L., Zheng, Y., Yuan, J., & Ng, K. W. (2017). Effects of hardness of steel on ceramic armour module against long rod impact. *International Journal of Impact*

Engineering, *109*, 419–426. https://doi.org/10.1016/j.ijimpeng.2017.08.004

Green, B. N., Johnson, C. D., & Adams, A. (2006). Writing narrative literature reviews for peer-reviewed journals: secrets of the trade. *Journal of Chiropractic Medicine*, *5*(3), 101–117. https://doi.org/10.1016/S0899-3467(07)60142-6

Grujicic, M., Bell, W. C., & Pandurangan, B. (2012). Design and material selection guidelines and strategies for transparent armor systems. *Materials and Design*, *34*, 808–819. https://doi.org/10.1016/j.matdes.2011.07.007

Hohler, V., Stilp, A. J., & Weber, K. (1995). Hypervelocity penetration of tungsten sinter-alloy rods into aluminum. *International Journal of Impact Engineering*, *17*, 409–418.

Holmquist, T. J., & Johnson, G. R. (2005). Modeling prestressed ceramic and its effect on ballistic performance. *International Journal of Impact Engineering*, *31*(2), 113–127. https://doi.org/10.1016/j.ijimpeng.2003.11.002

Jinzhu, L., Liansheng, Z., & Fenglei, H. (2017). Experiments and simulations of tungsten alloy rods penetrating alumina ceramic/603 armor steel composite targets. *International Journal of Impact Engineering*, *101*, 1–8. https://doi.org/10.1016/j.ijimpeng.2016.09.009

Lee, J., Oh, I., Jang, J., Hong, S., & Park, H. (2019). Mechanical properties and microstructural evolution of WC binderless and WC-Co hard materials by the heat treatment process. *Journal of Alloys and Compounds*, *786*, 1–10.

Levy, Y., & Ellis, T. J. (2006). A systems approach to conduct an effective literature review in support of information systems research. *Informing Science*, *9*(May 2014), 181–211. https://doi.org/10.28945/479

Liu, K., Wang, Z., Yin, Z., Cao, L., & Yuan, J. (2018). Effect of Co content on microstructure and mechanical properties of ultrafine grained WC-Co cemented carbide sintered by spark plasma sintering. *Ceramics International*, *44*(15), 18711–18718. https://doi.org/10.1016/j.ceramint.2018.07.100

Liu, W., Chen, Z., Cheng, X., Wang, Y., Amankwa, A. R., & Xu, J. (2016). Design and ballistic penetration of the ceramic composite armor. *Composites Part B: Engineering*, *84*, 33–40. https://doi.org/10.1016/j.compositesb.2015.08.071

Lundberg, P., & Lundberg, B. (2005). Transition between interface defeat and penetration for tungsten projectiles and four silicon carbide materials. *International Journal of Impact Engineering*, *31*(7), 781–792. https://doi.org/10.1016/j.ijimpeng.2004.06.003

Lundberg, P., Renström, R., & Lundberg, B. (2000). Impact of metallic projectiles on ceramic targets: Transition between interface defeat and penetration. *International Journal of Impact Engineering*, *24*(3), 259–275. https://doi.org/10.1016/S0734-743X(99)00152-9

Luo, D., Wang, Y., Wang, F., Cheng, H., Zhang, B., & Zhu, Y. (2020). The influence of metal cover plates on ballistic performance of silicon carbide subjected to large-scale tungsten projectile. *Materials and Design*, *191*, 108659. https://doi.org/10.1016/j.matdes.2020.108659

Moynihan, T. J., Chou, S.-C., & Mihalcin, A. L. (2000). *Application of the Depth-of-Penetration Test Methodology to Characterize Ceramics for Personnel Protection*.

National Institute of Justice. (2014). *Selection and Application Guide to Ballistic-Resistant Body Armor*.

National Research Council. (2012). Testing of Body Armor Materials: Phase III. In *Testing of Body Armor Materials: Phase III*. The National Academic Press. https://doi.org/10.17226/13390

Ning, J., Ren, H., Guo, T., & Li, P. (2013). Dynamic response of alumina ceramics impacted by long tungsten projectile. *International Journal of Impact Engineering*, *62*, 60–74. https://doi.org/10.1016/j.ijimpeng.2013.06.006

Orphal, D. L., & Franzen, R. R. (1997). Penetration of confined silicon carbide targets by tungsten long rods at impact velocities from 1.5 to 4.6 km/s. *International Journal of Impact Engineering*, *19*(1), 1–13. https://doi.org/10.1016/0734-743x(95)00064-h

Pare, G., & Kitsiou, S. (2016). Methods for Literature Reviews. In *Handbook of eHealth Evaluation: An Evidence-based Approach* (pp. 157–180). University of Victoria.

Reaugh, J. E., Holt, A. C., Wilkins, M. L., Cunningham, B. J., Hord, B. L., & Kusubov, A. S. (1999). Impact studies of five ceramic materials and pyrex. *International Journal of Impact Engineering*, *23*(1 PART II), 771–782. https://doi.org/10.1016/s0734-743x(99)00121-9

Robertson, C., & Hazell, P. J. (2003). Resistance of different ceramic materials to penetration by a tungsten carbide cored projectile. In *Ceramic Armor and Armor Systems* (pp. 153–163). The American Ceramic Society. https://doi.org/10.1002/9781118406793

Rosenberg, Z., Dekel, E., Hohler, V., Stilp, A. J., & Weber, K. (1997). Penetration of tungsten-alloy rods into composite ceramic targets: Experiments and 2-D simulations. *Shock Compression of Condensed Matter*, 917–920. https://doi.org/10.1063/1.55612

Rozenberg, Z., & Yeshurun, Y. (1988). The relation between ballastic efficiency and compressive strength of ceramic tiles. *International Journal of Impact Engineering*, *7*(3), 357–362. https://doi.org/10.1016/0734-743X(88)90035-8

Ruys, A. (2019). Alumina in lightweight body armor. In *Alumina Ceramics* (pp. 321–368). Elsevier Ltd. https://doi.org/10.1016/b978-0-08-102442-3.00011-7

Saeedi Heydari, M., Ghezavati, J., Abbasgholipour, M., & Mohammadi Alasti, B. (2017). Various types of ceramics used in radome: A review. *Scientia Iranica*, *24*(3), 1136–1147. https://doi.org/10.24200/sci.2017.4095

Sylvester, A., Tate, M., & Johnstone, D. (2013). Beyond synthesis: Re-presenting heterogeneous research literature. *Behaviour and Information Technology*, *32*(12), 1199–1215. https://doi.org/10.1080/0144929X.2011.624633

Tan, Z. H., Han, X., Zhang, W., & Luo, S. H. (2010). An investigation on failure mechanisms of ceramic/metal armour subjected to the impact of tungsten projectile. *International Journal of Impact Engineering*, *37*(12), 1162–1169. https://doi.org/10.1016/j.ijimpeng.2010.07.004

Westerling, L., Lundberg, P., & Lundberg, B. (2001). Tungsten long-rod penetration into confined cylinders of boron carbide at and above ordnance velocities. *International Journal of Impact Engineering*, *25*(7), 703–714. https://doi.org/10.1016/S0734-

743X(00)00072-5

Woodward, R. L., Gooch, W. A., O'Donnell, R. G., Perciballi, W. J., Baxter, B. J., & Pattie, S. D. (1994). A study of fragmentation in the ballistic impact of ceramics. *International Journal of Impact Engineering*, *15*(5), 605–618. https://doi.org/10.1016/0734-743X(94)90122-2

Yulong, H., & Fan, J. (1996). Development and current status of armor ceramics. *Ordnance Materials Science and Engineering*, *5*, 37–42.

Appendix

Table 1. Impact Velocity and DoP was Generating of Penetration on Boron Carbide by Tungsten Based Projectile

Author	Tungsten Based Material				Front of Main Target Material			Main Target Material				Backing of Main Target Material			Impact Velocity (m/s)	DoP (mm)
	Material Type	Hardness (GPa)	Density (kg/m³)	Dimension	Material Type	Hardness (Gpa)	Thickness (mm)	Material Type	Density (kg/m³)	Hardness (GPa)	Thickness (mm)	Material Type	Hardness (GPa)	Thickness (mm)		
Reaugh et al. (1999)	Tungsten Alloy	31.0	18360	length= 25.4 mm; diameter = 6.35 mm	N/A	N/A	N/A	Boron Carbide	2510	N/A	10.4 19.3 28.0 17.6	4340 Steel	3.8	64.0	1790 1740 1280 1220	28.3 19.8 13.3 3.8
Westerling et al. (2001)	Tungsten Heavy Alloy	N/A	17600	length= 150 mm; diameter = 2 mm	SIS 2541-3	3.2	1 1 1 1 2 2 2 2 2 4	Boron Carbide	2490	33.0	39.6	-	-	-	2601 2565 1517 1502 2555 2500 1787 1581 1454 1480	37.1 34.9 31.0 27.0 34.7 33.3 36.5 33.2 14.0 21.0
Rosenberg et al. (1997)	Tungsten Heavy Alloy	N/A	17600	length= 72.5 mm; diameter = 5.80 mm	-	-	-	Boron Carbide	2500	N/A	48.45	HH-RHA	4.5	100.0	1700	32.0
Robertson and Hazell (2003)	Tungsten Carbide Cobalt (5C83.5W-11Co-0.5Fe)	12.0	N/A	Projectile of 7.62 × 51 mm FFV Bullet Munition	-	-	-	Boron Carbide	2500	32.0	6.5	Al - 6082 T651	0.9	75.0	973	9.1

Source: Processed by Authors, 2020

Table 2. Impact Velocity and DoP was Generating of Penetration on Silicon Carbide by Tungsten Based Projectile

Author	Tungsten Based Material				Front of Main Target Material			Main Target Material				Backing of Main Target Material			Impact Velocity (m/s)	DoP (mm)
	Material Type	Hardness (GPa)	Density (kg/m³)	Dimension	Material Type	Hardness (GPa)	Thickness (mm)	Material Type	Density (kg/m³)	Hardness (GPa)	Thickness (mm)	Material Type	Hardness (GPa)	Thickness (mm)		
Lundberg and Lunberg (2005)	Tungsten Heavy Alloy	N/A	17600	length = 80 mm; diameter = 2 mm	OFHC Copper	N/A	8.0	SiC-B	N/A	25.20	20.0	Steel - Maraging 350	N/A	14.0	2064	17.0
															2049	13.1
															1917	12.9
															1809	16.0
															1766	14.2
															1745	15.5
															1669	14.2
								SiC-HPN		25.32					1749	18.0
															1673	16.0
															1636	15.0
								SiC-N		27.16					1618	11.0
															1602	12.2
															1576	11.8
															1572	15.7
															1556	12.6
															1529	13.0
															1502	14.5
								SiC-SC-1RN		28.85					1650	14.2
															1586	9.8
															1582	12.5
															1569	14.5
															1567	13.0
															1551	12.6
Lundberg, Renstrom, and Lundberg (2000)	Tungsten Heavy Alloy	N/A	17600	length= 80 mm; diameter = 2 mm	SIS 2541-3	3.2	8.0	SiC 1 (PAD Method)	3220	21.6	20.0	SIS 2541-3	3.2	10.0	2175	17.0
															1845	12.0
															1705	15.0
															1645	11.5
								SiC 2 (HIP Method)	3180	20.3					1805	16.0
															1715	14.0
Behner, Heine, and Wickert (2016)	Tungsten Heavy Alloy (W - Ni - Fe)	4.7	17600	length = 90 mm; diameter = 6	Copper	0.8	3.0	SiC-F (Buffered)	3220	26.0	25.0	RHA	3.4	40.0	1837	62.4*
															1678	15.9
															1478	19.5

				mm												*
															1211	23.8*
															1203	14.9*
															1200	17.4*
															1194	14.9*
															1019	6.8
					-	-	0.0	SiC (Bare)							1525	45.0*
															1356	35.2*
															1205	28.9*
															988	12.7
															891	6.6
															773	4.8
															593	1.1
															525	1.7
															380	0.4
Luo et al. (2020)	Tungsten Heavy Alloy	N/A	17600	length = 40 mm; diameter = 16 mm; with conical tip (length = 5 mm; diameter = 3.5 mm; angle = 40 degree)	No Cover	0.0	0	SiC	3160	N/A	30	RHA	N/A	30	1234	8.8*
					No Cover	0.0	0								1256	9.8*
					Aluminium Alloy	0.7	3								1245	2.0*
					Aluminium Alloy	0.7	3								1261	1.5*
					Aluminium Alloy	0.7	3								1266	0.8*
					Mild Steel	1.4	3								1247	4.3*
					Mild Steel	1.4	3								1261	5.2*
					Copper Alloy	1.2	3								1240	3.3*
					Copper Alloy	1.2	3								1247	3.7*

Orphal and Franzen (1997)	Tungsten (99.95%)	N/A	19300	length = 15.21 mm; diameter = 0.762 mm	Aluminum (6061-T6)	1.1	3.75	SiC (Cercom Inc.)	3220	26.0	48.26	Aluminum (6061-T6)	1.1	15.24	3445	31.4
Cao et. al. (2008)	Tungsten	N/A	N/A	N/A	-	-	-	SiC	3090	N/A	26	-	-	-	1400	13.0

Source: Processed by Authors, 2020

Table 3. Impact Velocity and DoP was Generating of Penetration on Alumina by Tungsten Based Projectile

Author	**Tungsten Based Material**				**Front of Main Target Material**			**Main Target Material**				**Backing of Main Target Material**			**Impact Velocity (m/s)**	**DoP (mm)**
	Material Type	**Hardness (GPa)**	**Density (kg/m³)**	**Dimension**	**Material Type**	**Hardness (GPA)**	**Thickness (mm)**	**Material Type**	**Density (kg/m³)**	**Hardness (GPa)**	**Thickness (mm)**	**Material Type**	**Hardness (GPa)**	**Thickness (mm)**		
Hohler et al (1995)	Tungsten Heavy Alloy	4.2	17600	pointed; length = 72.5 mm; diameter = 5.8 mm	Rubber Foil	N/A	1.5	Alumina (Al_2O_3)	3800	21	19.8	Steel (HH-RHA)	4.4	60	1246	17.5
											39.6				1246	5.0
											59.8				1252	0.0
											59.6				1698	15.2
											61.1				1702	16.7
											20.2				1705	42.6
											81.4				1705	4.2
											60.0				1706	14.5
											79.0				1708	2.2
											40.1				1709	28.9
											19.9				1710	44.6
											80.7				1710	4.6
											39.5				1711	30.2
											40.6				1711	29.7
											80.0				1716	2.8
											20.0				1717	43.4
											60.0				1717	14.7
											40.0				1721	31.7
		5.35		pointed; length = 49.5 mm; diameter = 5 mm	Rubber Foil	N/A	1.5	Alumina (Al_2O_3)	3800	21	70.0	Steel (HH-RHA)	4.4	60	2516	10.2
											20.0				2522	50.7
											30.0				2537	39.1
											50.0				2550	23.9
											10.0				2552	60.2
											100.5				2963	0.0

											101.2				2964	0.0
											19.6				2968	58.8
											69.8				2980	18.7
											20.5				2984	58.1
											40.8				2991	38.6
											10.0				2994	68.0
											40.4				2995	41.3
											80.8				2995	9.0
											81.1				2998	8.8
											30.8				3000	50.2
											41.1				3000	40.1
											19.9				3002	58.3
											82.0				3003	7.5
											10.0				3023	67.0
											10.0				3024	66.8
											30.0				3025	50.0
											62.0				3037	21.6
Jinzhu et al (2016)	Tungsten Heavy Alloy	N/A	17540	pointed; length = 120 mm; diameter = 5.6 mm	-	-	-	Alumina 99.5%	3890	14.7	90.0	603 Armor Steel	N/A	80.0	1554	35.0
															1575	10.0
															1577	55.0
															1577	33.0
															1600	72.0
															1611	73.0
Ning et al (2013)	Tungsten Alloy	N/A	19200	length = 45 mm; diameter = 4.5 mm	Steel	N/A	10.2	AD-90 (89.8% Al_2O_3 + 7.8% SiO_2 + 2.2% CaO)	3625	N/A	29.9	N/A	N/A	N/A	2310	41.7
							10.3								2298	41.0
							10.2								2312	39.0
							10.2								2300	50.0
					No Cover Steel		0.0								2319	55.0
							10.2								1720	26.8
							10.2								1690	31.0
							10.3								1910	42.1
							10.2								2315	29.2
Tan et al (2010)	Tungsten Alloy	N/A	N/A	length = 29 mm; diameter = 7.62 mm	4340 Steel	N/A	5	AD-95 Ceramic	3600	N/A	11.0	4340 Steel	N/A	8	823	3.6
							5							8	826	4.9
							5							13	818	2.9
							N/A							13	824	4.2

Carton et al (2019)	Tungsten Carbide (WC)	N/A	N/A	length = ~40 mm; diameter 6.2 mm; 7.62 AP8 type	-	-	-	Alumina (Al_2O_3)	N/A	N/A	8.0	Polycarbonate Cubes	N/A	N/A	899 902 900 902 901 899	39 37.7 43.4 44.1 40.8 41.1
Basyir et al (2019)	Tungsten Carbide-Cobalt (WC-8Co)	16.43	14800	length = ~20 mm; diameter = 5.56 mm	-	-	-	Alumina (Al_2O_3)	3940	14.7	10.0	Plasticine (Clay)	N/A	150.0	885 875 871	57.54 53.17 48.64

Source: Processed by Authors, 2020

Table 4. Impact Velocity and DoP was Generating of Penetration on Titanium Diboride by Tungsten Based Projectile

Author	Tungsten Based Material				Front of Main Target Material			Main Target Material				Backing of Main Target Material			Impact Velocity (m/s)	DoP (mm)
	Material Type	**Hardness (GPa)**	**Density (kg/m^3)**	**Dimension**	**Material Type**	**Hardness (GPA)**	**Thickness (mm)**	**Material Type**	**Density (kg/m^3)**	**Hardness (GPa)**	**Thickness (mm)**	**Material Type**	**Hardness (GPa)**	**Thickness (mm)**		
Woodward et al. (1994)	Tungsten Alloy	N/A	N/A	pointed; diameter = 7.72 mm; mass = 23.2 gram	-	-	-	Titanium Diboride – Ceradyne Grade	4520	27.0	12.7	Al Alloy 2024-T351 Type	N/A	6.35	1209	38.0
Reaugh et al. (1999)	Tungsten Alloy	31.0	18360	length = 25.4 mm; diameter = 6.35 mm	-	-	-	Titanium Diboride	4490	N/A	10 14.9 30.3 40	4340 Steel	3.8	64	1310 1700 2630 2630	3.7 7.3 17.8 9.6
Rosenberg et al. (1997)	Tungsten Heavy Alloy	N/A	17600	length = 72.5 mm; diameter = 5.80 mm	-	-	-	Titanium Diboride	4450	N/A	19.8 39.6 50.3 59.4	HH-RHA	4.5	100	1700 1700 1700 1700	34.5 19.6 8.0 6.2
Lundberg, Renstrom, and	Tungsten Heavy Alloy	N/A	17600	length = 80 mm; diameter = 2 mm	SIS 2541-3	3.2	8.0	Titanium Diboride	4400	20.6	20.0	SIS 2541-3	3.2	10.0	1615 1545 2370	12.0 10.0 18.5

Lundberg (2000)	1465	2.0
	2500	17.0
	2135	15.0
	1940	13.5

Source: Processed by Authors, 2020

Table 5. Data of Impact Velocity versus DoP by Tungsten Alloy Projectile on Boron Carbide, Silicon Carbide, Alumina, and Titanium Diboride

Material Type of Main Target	Projectile				Target						Impact Velocity (m/s)	Total DoP (mm)
					Front Target		Main Target		Backing Target			
	Material Type	Density (kg/m3)	Hardness (Gpa)	Dimension	Thickness (mm)	Material Type	Thickness (mm)	Density (Kg/m3)	Thickness (mm)	Hardness (Gpa)		
B4C	Tungsten Alloy	17600	4.2	length = 72.5 mm; diameter = 5.8 mm	-	-	48.5	2500.0	100	4.5 (HH-RHA Steel)	1700	32.0
SiC	Tungsten Alloy	17600	4.2	length = 80 mm; diameter = 2 mm	8	SIS 2541-3	20.0	3220.0	10	3.2 (SIS 2541-3)	1705	23.0
Alumina	Tungsten Alloy	17600	4.2	length = 72.5 mm; diameter = 5.8 mm	1.5	Rubber Foil	20.0	3800.0	60	4.5 (HH-RHA Steel)	1702	42.6
TiB2	Tungsten Alloy	17600	4.2	length = 72.5 mm; diameter = 5.8 mm	-	-	19.8	4450.0	100	4.5 (HH-RHA Steel)	1700	34.5

Source: Processed by Authors, 2020