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

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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 (Bramante 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$_2$O$_3$), boron carbide (B$_4$C), 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 (B₄C)
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 & Hazel, 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](image-url)  
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 (B4C)

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
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 B₄C 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/m³ had smaller penetration resistance than SiC with a density of 3220 kg/m³. Although, the impact velocity on SiC with a density of 3220 kg/m³ was bigger than on SiC with a density of 3090 kg/m³. 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 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/m³.

**The Target Material of Alumina (Al₂O₃)**

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/m³ 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/m³ 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/m³ 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/m³ and a hardness of 16.43 GPa. Moreover, the main target was alumina with a density of 3940 kg/m³ 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.
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 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 ($\text{Al}_2\text{O}_3$) 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 ($\text{TiB}_2$)

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](image.png)

**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 B₄C 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 B₄C, even though the B₄C in this experiment had steel (SIS 2541-3 type) as cover material.

Therefore, although from the mechanical properties data, B₄C 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 B₄C since this material had superior in bending strength and fracture toughness (increasing of density), compared to B₄C.

Moreover, from almost the same impact velocity and dimension of a projectile, the boron carbide had the best penetration resistance than TiB₂ and Al₂O₃ (see Figure 5). It was because bending strength, yield strength, and hardness of B₄C were superior if compared to TiB₂ and Al₂O₃. Furthermore, TiB₂ and Al₂O₃ had much bigger density than B₄C, where the increase of density enhanced fracture toughness but decreased on Young's modulus and hardness (Cui et al., 2017).

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 B₄C 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/m³, 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/m³, and impact velocity of 1805 m/s. Besides, the target configuration for this scheme was the main target with cover material (SIS 2541-3.
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$_4$C, TiB$_2$, and Al$_2$O$_3$. Besides, for almost similar projectile dimensions, the same material of projectile and target configuration, the minimum impact velocity to perforate the B$_4$C, SiC, Al$_2$O$_3$, 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.

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## 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) |
|--------------------|-------------------------|--------------------------------|----------------------|----------------------------------|-----------------------|----------|
| Reaugh et al.      | Tungsten Alloy          | 31.0                           | 18360                | N/A                             | 25.4                  | 3.8      | 64.0 | 1790 | 28.3 |
|                    |                         | length=25.4; diameter=6.35 mm   | N/A                  | N/A                             | 10.4                  | 6.8      | 90.1 | 1740 | 19.8 |
|                    |                         |                                | N/A                  | Boron Carbide                   | 19.3                  | 9.6      | 13.4 | 1280 | 13.3 |
|                    |                         |                                |                      |                                  | 28.0                  | 16.4     | 7.8  | 1240 | 13.0 |
|                    |                         |                                |                      |                                  | 17.6                  | 13.2     | 12.3 | 1200 | 3.8  |
| Westerling et al.  | Tungsten Heavy Alloy    | 31.0                           | 17600                | SIS 2541-3                       | 3.2                   | 1        | 1    | 1    | 1    |
|                    |                         | length=150 mm; diameter=2 mm   |                      |                                  | 1                     | 1        | 1    | 2    | 2    |
|                    |                         |                                |                      |                                  | 2                     | 2        | 2    | 2    | 2    |
|                    |                         |                                |                      |                                  | 4                     | 4        | 1    | 4    | 4    |
|                    |                         |                                |                      | Boron Carbide                    | 2490                  | 33.0     | 39.6 | 2601 | 37.1 |
|                    |                         |                                |                      |                                  |                       | -        | -    | 2565 | 34.9 |
|                    |                         |                                |                      |                                  |                       | -        | -    | 1517 | 31.0 |
|                    |                         |                                |                      |                                  |                       | -        | -    | 1502 | 27.0 |
|                    |                         |                                |                      |                                  |                       | -        | -    | 2555 | 34.7 |
|                    |                         |                                |                      |                                  |                       | -        | -    | 2500 | 33.3 |
|                    |                         |                                |                      |                                  |                       | -        | -    | 1787 | 36.5 |
|                    |                         |                                |                      |                                  |                       | -        | -    | 1581 | 33.2 |
|                    |                         |                                |                      |                                  |                       | -        | -    | 1454 | 14.0 |
|                    |                         |                                |                      |                                  |                       | -        | -    | 1480 | 21.0 |
| Rosenberg et al.   | Tungsten Heavy Alloy    | 31.0                           | 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 |
| Roberts on and Hazell| Tungsten Carbide         | 12.0                           | N/A                  | Projectile of 7.62 × 51 mm FFV  | Boron Carbide         | 2500      | 32.0 | 6.5   | Al - 6082 T651 | 0.9  | 75.0 | 973  | 9.1  |
| (2003)             | Cobalt (5C83.5W-11Co-0.5Fe) |                                |                      |                                  |                       | -         | -    |       |       |      |      |      |      |

**Source:** Processed by Authors, 2020
| Author                                      | Tungsten Based Material | Front of Main Target Material | Main Target Material | Backing of Main Target Material | Impact Velocity (m/s) | DoP (mm) |
|---------------------------------------------|-------------------------|-------------------------------|---------------------|---------------------------------|-----------------------|----------|
| Lundberg and Lunberg (2005)                | Tungsten Heavy Alloy    | N/A                           | 1760                | OFHC Copper                      | 8.0                   | SiC-B    |
|                                             |                         |                               |                     |                                 | 25.20                 | 20.0     |
|                                             |                         |                               |                     | Steel - Maraging 350            | N/A                   | 14.0     |
|                                             |                         |                               |                     |                                 | 2064                  | 17.0     |
|                                             |                         |                               |                     |                                 | 2049                  | 13.1     |
|                                             |                         |                               |                     |                                 | 1809                  | 16.0     |
|                                             |                         |                               |                     |                                 | 1766                  | 14.2     |
|                                             |                         |                               |                     |                                 | 1745                  | 15.5     |
|                                             |                         |                               |                     |                                 | 1669                  | 14.2     |
|                                             |                         |                               |                     |                                 | 1749                  | 18.0     |
|                                             |                         |                               |                     |                                 | 1673                  | 16.0     |
|                                             |                         |                               |                     |                                 | 1636                  | 15.0     |
|                                             |                         |                               |                     |                                 | 1618                  | 11.0     |
|                                             |                         |                               |                     |                                 | 1602                  | 12.2     |
|                                             |                         |                               |                     |                                 | 1576                  | 11.8     |
|                                             |                         |                               |                     |                                 | 1572                  | 15.7     |
|                                             |                         |                               |                     |                                 | 1556                  | 12.6     |
|                                             |                         |                               |                     |                                 | 1529                  | 13.0     |
|                                             |                         |                               |                     |                                 | 1502                  | 14.5     |
|                                             |                         |                               |                     |                                 | 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                           | 1760                | SIS 2541-3                       | 3.2                   | 8.0      |
|                                             |                         |                               |                     | SiC 1 (PAD Method)              | 3220                  | 21.6     |
|                                             |                         |                               |                     |                                 | 20.0                  | 3220     |
|                                             |                         |                               |                     | SIS 2541-3                       | 3.2                   | 10.0     |
|                                             |                         |                               |                     |                                 | 2175                  | 17.0     |
|                                             |                         |                               |                     |                                 | 1845                  | 12.0     |
|                                             |                         |                               |                     |                                 | 1705                  | 15.0     |
|                                             |                         |                               |                     |                                 | 1645                  | 11.5     |
|                                             |                         |                               |                     |                                 | 1805                  | 16.0     |
|                                             |                         |                               |                     |                                 | 1715                  | 14.0     |
| Behner, Heine, and Wickert (2016)           | Tungsten Heavy Alloy    | N/A                           | 1760                | Copper                          | 0.8                   | 3.0      |
|                                             |                         |                               |                     |                                 | 3220                  | 26.0     |
|                                             |                         |                               |                     |                                 | 25.0                  | RHA      |
|                                             |                         |                               |                     |                                 | 3.4                   | 40.0     |
|                                             |                         |                               |                     |                                 | 1837                  | 62.4     |
|                                             |                         |                               |                     |                                 | 1678                  | 15.9     |
|                                             |                         |                               |                     |                                 | 1478                  | 19.5     |
| Luo et al. (2020) | Tungsten Heavy Alloy | N/A | 1760 | length = 40 mm; diameter r = 16 mm; with conical tip (length = 5 mm; diameter r = 3.5 mm; angle = 40 degree) | No Cover | No Cover | Aluminium Alloy | Aluminium Alloy | Aluminium Alloy | Mild Steel | Mild Steel | Copper Alloy | Copper Alloy |
|------------------|-----------------------|-----|------|-----------------------------------------------------------------------------------------------------------------|---------|---------|-----------------|-----------------|----------------|-------------|-------------|--------------|--------------|
|                  |                       |     |      |                                                                                                                 | 0.0     | 0.0     | 0.7             | 0.7             | 0.7            | 1.4         | 1.4         | 1.2          | 1.2          |
|                  |                       |     |      | SiC (Bare)                                                                                                       | 0.0     | 0.0     | 0.7             | 0.7             | 0.7            | 1.4         | 1.4         | 1.2          | 1.2          |
|                  |                       |     |      | 3160                                                                                                             | N/A     | N/A     | N/A             | N/A             | N/A            | N/A         | N/A         | N/A          | N/A          |
|                  |                       |     |      | 30                                                                                                               | RHA     | RHA     | RHA             | RHA             | N/A            | 30          | 30          | 30           | 30           |
|                  |                       |     |      | RHA                                                                                                              | N/A     | N/A     | N/A             | N/A             | N/A            | 30          | 30          | 30           | 30           |
|                  |                       |     |      | 1234                                                                                                             | 8.8*    | 9.8*    | 2.0*            | 1.5*            | 0.8*           | 4.3*        | 5.2*        | 3.3*         | 3.7*         |
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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) |
|-----------------------|-------------------------|-------------------------------|---------------------|---------------------------------|-----------------------|----------|
| Hohler et al. (1995) | Tungsten (99.95%)       | N/A                           | N/A                 | N/A                             | 1400                  | 13.0     |
|                       | N/A                     | N/A                           | N/A                 | N/A                             | 3090                  | N/A      |
|                       | N/A                     | N/A                           | N/A                 | N/A                             | 26                    | N/A      |
|                       | N/A                     | N/A                           | N/A                 | N/A                             | 1400                  | 13.0     |
| Cao et. al. (2008)   | Tungsten                | N/A                           | N/A                 | N/A                             | 1400                  | 13.0     |
|                       | N/A                     | N/A                           | N/A                 | N/A                             | 3090                  | N/A      |
|                       | N/A                     | N/A                           | N/A                 | N/A                             | 26                    | N/A      |
|                       | N/A                     | N/A                           | N/A                 | N/A                             | 1400                  | 13.0     |
| Source: Processed by Authors, 2020

Table constructed using the data from the given text. The table includes columns for Author, Tungsten Based Material, Front of Main Target Material, Main Target Material, Backing of Main Target Material, Impact Velocity (m/s), and DoP (mm). The data is divided into rows, each representing a different author and their corresponding materials, impact velocity, and depth of penetration (DoP). The table is intended to demonstrate the impact velocity and DoP generated by Tungsten-based projectiles on Alumina targets. The table is annotated with specific experimental conditions and materials used in the tests. The data is sourced from various publications, including Orphal and Franzen (1997), Hohler et al. (1995), and Cao et al. (2008).
| Author(s)          | Alloy Type     | N/A | Length (mm) | Diameter (mm) | Material Composition | Density (g/cm³) | Tensile Strength (MPa) | Yield Strength (MPa) | Elongation (%) |
|-------------------|----------------|-----|-------------|---------------|----------------------|----------------|------------------------|---------------------|-----------------|
| 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 |
| Ning et al (2013)  | Tungsten Alloy  | N/A | 19200 length = 45 mm; diameter = 4.5 mm | Steel | N/A | AD-90 (89.8% Al₂O₃ + 7.8% SiO₂ + 2.2% CaO) | 3625 | N/A | 29.9 | N/A | N/A | N/A | 2310 | 41.7 |
| Tan et al (2010)   | Tungsten Alloy  | N/A | N/A | 4340 Steel | N/A | AD-95 Ceramic | 3600 | N/A | 11.0 | 4340 Steel | N/A | 8 | 823 | 3.6 |

101.2 19.6 69.8 20.5 40.8 10.0 40.4 80.8 81.1 30.8 41.1 19.9 82.0 10.0 30.0 62.0 101.2 19.6 69.8 20.5 40.8 10.0 40.4 80.8 81.1 30.8 41.1 19.9 82.0 10.0 30.0 62.0 101.2 19.6 69.8 20.5 40.8 10.0 40.4 80.8 81.1 30.8 41.1 19.9 82.0 10.0 30.0 62.0
| Author                      | Tungsten Based Material | Front of Main Target Material | Main Target Material | Backing of Main Target Material | Impact Velocity (m/s) | DoP (mm) |
|-----------------------------|-------------------------|------------------------------|----------------------|--------------------------------|----------------------|---------|
| Carton et al (2019)         | Tungsten Carbide (WC)   | N/A                          | N/A                  | Alumina (Al₂O₃)                | 8.0                  | Polycarbonate Cubes N/A | 308     |
| Basyir et al (2019)         | Tungsten Carbide-Coalt (WC-8Co) | 16.43 | 14800 | length = ~20 mm; diameter = 5.56 mm | Alumina (Al₂O₃) | 3940 | 14.7 | 10.0 | Plasticine (Clay) | N/A | 150.0 | 885 | 57.5 |

Source: Processed by Authors, 2020

Table 4. Impact Velocity and DoP was Generating of Penetration on Titanium Diboride by Tungsten Based Projectile
### 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 | Material Type | Density (kg/m³) | Hardness (Gpa) | Dimension | Front Target | Main Target | Backing Target | Impact Velocity (m/s) | Total DoP (mm) |
|-----------------------------|---------------|-----------------|----------------|-----------|--------------|-------------|-----------------|------------------------|----------------|
| 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*