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Original research article

Composition, Microstructure, Hardness and Ballistic Properties of a Representative Steel versus Kevlar Military

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ABSTRACT

Ballistic helmets are essential for protecting against projectiles, fragmentation, and blunt trauma—key contributors to combat fatalities. This study compares the ballistic performance, durability, and cost-efficiency of a tempered martensite steel helmet to a modern Kevlar composite helmet. Through ballistic, mechanical, and metallographic testing, the steel helmet demonstrated comparable protection against pistol and revolver calibers, due to ballistic shape and high quality of steel applied. However, against rifle calibers, both helmets performed similarly, with perforations by 5.56x45 mm and 7.62x39 mm. The paper examines the trade-offs between protection, durability, and cost, highlighting steel helmets as a viable alternative in contemporary protective gear.

Key words: *Military helmets; ballistic protection; mechanical properties; steel; composite.*

1. Introduction

Ballistic helmets are a critical part of personal protective equipment, providing protection against projectiles, fragmentation, and blunt trauma [1]. Although the head accounts for only 9–12% of the body exposed in combat, head injuries are responsible for around 50% of combat fatalities [2, 3]. During WWI, several iconic steel helmets were developed: the French Adrian M15, British Brodie, and German Stahlhelm M1916 [2]. The Adrian helmet, made of 0.8 mm mild steel and weighing 750 g, was lightweight, easy to produce, and effective against top-down blast threats [3]. The British Brodie, introduced in 1915, prioritized protection from overhead shrapnel with its shallow, wide-brimmed shape. Made of Hadfield steel and weighing up to 1100 g [2]. In contrast, the German M1916 Stahlhelm offered superior protection with its deeper profile and tempered martensitic structure. Made from a Mn-Si-Ni alloy, it was 1.0–1.1 mm thick, and weighed ~ 1200 g with liner [2]. After WWI, helmet production standardized around two materials: austenitic manganese steel and tempered martensitic steel [4]. Austenitic Mn-steel remained ductile in cold climates and was non-magnetic, avoiding compass interference. Tempered martensite provided higher hardness and ballistic resistance in moderate and hot conditions. These materials dominated until the introduction of composites in the 1970s–1980s [5]. Modern ballistic helmets predominantly utilize polymeric materials such as Kevlar and ultra-high molecular weight polyethylene (UHMWPE), with an increased stated impact velocity, their main disadvantage is their shelf-life, which is usually limited to five to ten years [6]. In this work, a steel helmet with a tempered martensitic microstructure was tested and compared to a representative Kevlar helmet. Ballistic, mechanical, and metallographic tests were performed in order to assess the competitiveness of steel versus composite material.

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2. EXPERIMENTAL PART

The helmets analyzed in this paper are M56/76 helmet originating from former East Germany was introduced in the 1970s, and Advanced Combat Helmet (ACH), introduced in 2007, which serves as a modern counterpart for the comparison in this study (Fig. 1).

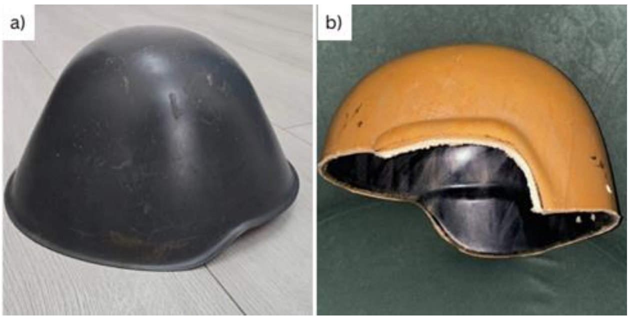

Fig 1 *(a) M56/76; (b) ACH*

Characterization of the M56/76 steel helmet was performed by: microstructural observation, microhardness, chemical composition, and ballistic testing. Metallographic samples from the M56/76 helmet were firstly prepared by grinding using SiC abrasive papers (P120 to P2000 grit), polished with diamond suspensions (6, 3, 1, and ¼ µm), and etched in 3% Nital (3% HNO_3 in ethanol). Microstructural examination was done by a JEOL JSM6460LV scanning electron microscope (SEM) operating at 20 kV. Before SEM analysis, the specimens were coated with gold by the Ball-Tech Leica SCD-005 device. The chemical composition of the M56/76 helmet was determined using optical emission spectrometer (OES) using G.N.R. MicroLab 150. The helmet specimens were first cut and ground with P120 SiC abrasive paper. Microhardness testing was done on a Wilson Tukon 1103 device, with indenter load of 1000 g.

Fig. 2 *Helmet setup system*

Ballistic tests were conducted under clear weather conditions, with an ambient temperature of 19 °C. The helmets were mounted on three wooden stakes hammered into the ground and supported with tires to provide a semi-elastic response, Figure 2. Shooting was conducted from a distance of 10 m.

Firearms used during testing are shown in Figure 3. The applied pistols and rifles, as well as their ammunition type and basic ballistic properties are as follows:

1. Smith Wesson M&P15 carbine with 406 mm (16 in) barrel chambered in 5.56x45 mm. Ammunition used was a 62 gr (4 g) FMJ SS109 with a steel tip penetrator and muzzle velocity of 880 m/s (Fig. 3a).
2. Zastava PAP-G carbine chambered in 7.62x39 mm, with a barrel length of 415 mm, firing a 123 gr (8 g) FMJ M67 lead-cored projectile with a muzzle velocity of 720 m/s (Fig. 3a).
3. Just Right Carbine (JRC) chambered in 9x19 mm with muzzle velocity of 430 m/s (Fig. 3b).
4. Pistol CZ75 pistol, 9x19 mm Parabellum firing a 124 gr (8 g) and a 145 gr (9.3 g) Full Metal Jacket (FMJ) ammunition with a muzzle velocity of 315 m/s and 356 m/s respectively (Fig. 3c).
5. Ruger GP100 revolver chambered in .357 Magnum with FMJ 158 gr (10.2 g) ammunition, a muzzle velocity of 410 m/s (Fig. 3c).

a) b) c)

Fig. 3 *(a) M&P15 and PAP-G; (b) JRC and (c) CZ75 and Ruger GP100*

Backface deformation (BFD) caused by bullet impacts was using standard welding inspection gauges.

3. RESULTS AND DISCUSSION

3.1 Steel helmet characterization

Weight of the helmets was 1499 g for M56/76 and 1500 g for ACH [7], which makes them nearly identical. Protective shell thickness greatly differs, in M56/76 being 1.36 mm, while in ACH being 11 mm, due to a much lower density of the composite material.

Microstructural analysis is presented in Fig. 4. The results indicate that the M56/76 helmet consists of a fine tempered martensite. This offers adequate strength, hardness and ductility.

The microhardness values for the M56/76 helmets, obtained from the cross-section of the protective shell, are provided in Table 1. The average hardness of 571.4 HV1 correlates very well with the previously shown microstructure. Small deviation implies that the microstructure is homogeneous and signifies a high quality of the manufacturing process and material used.

Table 2 shows the results of chemical composition, obtained by OES.

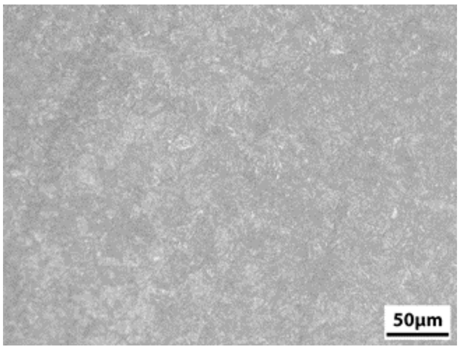

Fig. 4 *Microstructure of the M56/76 helmet*

Table 1 – *M56/76 microhardness values*

Indenter loading	Values	Average
HV1	578.4 573.1 562.7	571.4±8

Table 2 – *Chemical composition of the M56/76 helmet [mass %]*

C	Si	Mn	P	S	Cr	Ni
0.32	1.69	1.04	0.01	0.01	0.35	1.93

3.2 Ballistic testing results

Ballistic testing results of the M56/76 helmet are shown in Table 3. It can be observed that the helmet did not have many issues stopping the pistol calibre ammunition, with the greatest deformation occurring when shot from the rear with the .357 Magnum ammunition (15 mm). A statement could be made that the helmet also stopped the carbine fired 9x19 mm ammunition, although perforation did occur after getting hit multiple times in the same area. Such a phenomenon can be explained by a significant work hardening effect taking place after a ballistic impact, whereby the material experienced severe embrittlement, which let to cracking.
Both rifle calibre projectiles had no trouble perforating the helmet at a distance of 10 m. On the other hand, it must be considered that the helmet was not designed to provide protection from rifle calibre ammunition at such close ranges.
In the work by Brdar [5], ballistic properties for the ACH helmet were tested, under same conditions. They obtained quite similar results, where the helmet defeated all pistol caliber ammunition. At one point, a .357 Magnum projectile did strike the side of the helmet, where it created a BFD greater than 16 mm, which is defined by a standard as inducing lethal behind-armour blunt trauma. Furthermore, most of the BFD on the ACH helmet were greater than those found on the M56/76 helmet, with deformations on the steel helmet rarely exceeding 10 mm. Those results can be attributed to the sloping of the steel helmet, which in turn greatly increase the effectiveness of its ballistic resistance. It should be mentioned that such a design also allows for use of communication devices under the helmet, which is today considered as standard.
They tested the ACH helmet against same rifle caliber ammunition as well, and both projectile managed to perforate the helmet.

Table 3 – *Ballistic test results of the M56/76 helmet*

Shot no.	Caliber	Firearm	Results
1	9x19	CZ 75	No perforation, left side, deformation 6 mm
2	9x19	CZ 75	No perforation, left side, deformation 4 mm
3	9x19	CZ 75	No perforation, left side, deformation 5 mm
4	.357 Magnum	Ruger GP100	No perforation, rear, deformation 3 mm
5	.357 Magnum	Ruger GP100	No perforation, rear, deformation 15 mm
6	.357 Magnum	Ruger GP100	No perforation, rear deformation 3.5 mm
7	9x19	JRC	No perforation, right side, deformation 7 mm
8	9x19	JRC	No perforation, rear, deformation 9 mm
9	9x19	JRC	Perforation, near previous impacts, rear
10	5.56x45	M&P15	Perforation, front
11	5.56x45	M&P15	Perforation, front
12	7.62x39	PAP-G	Perforation, front

3.4 Fracture analyses via SEM

Fracture surfaces on the M56/76 helmet were SEM examined to determine the mode of fracture that occurred during the impact and subsequent failure of the steel. In Fig. 7, the presence of dimples clearly points to a ductile fracture mode. SEM imaging further reveals that these dimples are relatively small, consistent with a fine grain size.

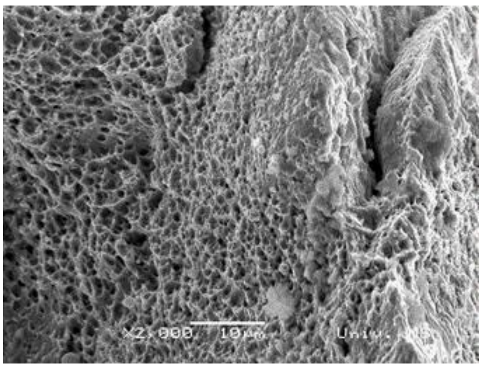

Fig. 7 *SEM image of M56/76 fractured surface*

4. CONCLUSIONS

Based on the results presented and the limitations of this study, the following conclusions can be drawn:

- The ballistic resistance of both the steel and composite helmets is similar against pistol caliber ammunition, with M56/76 experiencing smaller deformation, most likely due to sloping.
- High ballistic resistance of the M56/76 helmet can be attributed to the fine tempered martensite microstructure and the well-designed sloping.
- ACH helmet stopped all pistol ammunition, although .357 Magnum induced an unacceptable BFD.
- Assault rifle ammunition perforated both helmets with no significant issues. Future tests may reveal how the helmets would protect against such projectiles at longer ranges.

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