Determination of the Cause of the Differing Ballistic Performance of 9mm DM11 Bullets from Two Manufacturers

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Determination of the Cause of the Differing Ballistic Performance of 9mm DM11 Bullets from Two Manufacturers

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Abstract. In London, firearm threats faced by police during criminal activity include 9mm handguns and sub-machine guns. The UK Home Office body armour standards have included 9mm DM11 A1B2, manufactured originally by Dynamit Nobel under RWS branding, for over a decade. The recently published 2017 UK Home Office body armour standard continues to specify the 9mm DM11 A1B2, however, the specified manufacturer has changed to Metallwerk Elisenhütte GmbH (MEN). The DM11 A1B2 bullet comprises a copper coated steel full metal jacket with a lead core and bullets from both are specified to the same drawings and dimensional tolerances. However, during empirical testing against soft armour systems differences have been observed in the V_{mean} measured by CPA for the 2 bullets. As a result, body armour systems designed to pass the standard tests using the RWS 9mm DM11 A1B2 bullet manufactured may have a lesser safety margin when subject to impact with the equivalent MEN bullet. This paper reports on the results of an investigation in to the causes of the differing performance of the two sources of 9mm DM11 A1B2 bullets. It includes a study of the metallurgy of the steel jacket, dimensional and mass comparisons and a range of high strain rate testing to compare the properties and deformation behaviour of the two bullet types. Ballistic tests have been performed to demonstrate how the difference in performance may be related to the observed differences in the steel jacket metallurgy and the resulting differing deformation behaviour. The study has shown that the root cause of the differing performance is due primarily to differences in the steel used for the jackets by the different manufacturers. This work has important consequences for the UK body armour industry and others testing with the 9mm DM11 round.

1. INTRODUCTION

For over a decade the United Kingdom Home Office body armour standards for protection against ballistic threats [1] have included the 9 x 19mm FMJ DM11 A1B2 with a mass of 8.0 g (124 grains), supplied under the RWS brand and commonly referred to as Dynamit Nobel. The bullet had been manufactured by Dynamit Nobel under the brand RWS (Rheinisch-Westfälischen Sprengstoff-Fabriken) since 1931 but since 2002 the RWS brand has been owned and produced by RUAG Ammotec. In the Home Office standard this bullet is specified at different test velocities to meet 3 levels of protection, HG1/A, HG1 and HG2. A large number of ballistic protection products, primarily soft armour, have been designed and manufactured using this test standard and specific bullet. The RWS 9 x 19mm FMJ DM11A1B2 bullet is no longer in production by RUAG Ammotec and during the creation of the new Home Office standard [2] an alternative manufacturer was identified. Metallwerk Elisenhütte GmbH (MEN) currently manufacture a 9 x19mm FMJ DM11 A1B2 bullet, and this bullet is now incorporated into the new 2017 Home Office standard [2].

Following empirical test results, concern has been raised, among those responsible for armour specification and testing, that the two sources of 9 x 19mm FMJ DM11A1B2 bullets do not perform identically, despite being fabricated to an apparently identical specification. Factors that may affect ballistic performance of otherwise identical FMJ bullets include the properties of the lead core and steel jacket which in turn influence the resistance to deformation and the propensity for the jacket to fracture, leading to the formation of sharp jacket fragments. A bullet which resists deformation more readily may be able to penetrate more easily as it maintains a higher energy density at the point of contact with the armour. Conversely, a bullet with a steel jacket that more readily deforms and fractures may create sharp fragments of steel which could more readily defeat soft armour structures. This paper sets out to quantify the difference between the two bullets in terms of ballistic performance and to try and explain the difference in terms of the properties of the bullets, paying particular attention to the materials from which each is made.

In previous work on bullet deformation Maréchal [3] developed a method for the quantification of the deformation of 9mm FMJ Parabellum bullets after impacting with a hard steel plate at varying velocities (V). They describe the change in length (l) and diameter (d) of a deformed bullet by the deformation criteria C where:

$$C = \left(\frac{1}{2} \cdot \left[\left(\frac{\Delta l}{l_0}\right)^2 + \left(\frac{\Delta d}{d_0}\right)^2\right]\right)^{1/2} \quad (1)$$

where l_0 and d_0 are the length and diameter of the bullet before impact, l and d the same dimensions after impact and $\Delta l = l_0 - l$ and $\Delta d = d_0 - d$. In their experiment, they demonstrate that for 9mm FMJ Parabelum bullets as impact velocity increases then C increases in a linear manner (gradient 5.6×10^{-3} s m^{-1}) until a critical threshold in velocity is reached after which the gradient of the line is increased dramatically by a factor of 6. Above this threshold velocity the jacket fractures leading to much greater deformation of the bullet, with a 6 times higher gradient in the C v's V graph (3.4×10^{-2} s m^{-1}). For the bullets used in their experiment the threshold velocity for jacket fracture was observed to be 130 m s^{-1}.

Previous work by Thornby [4] has studied the RWS 9mm DM11 A1B2 bullets in order to quantify variations in the bullet's construction and inpartiucalr jacket thickness using CT scanning. They noted that jacket thickness varied from a maximum of approximately 500 μm near the tip to as low as 250 μm on the side wall. Radial variation in thickness was less than 13% on average. They used CT scans and ballistic tests against a hard steel plate (similar to Maréchal) to correlate ballistic performance and deformation behaviour. While the authors did not attempt the type of analysis performed by Maréchal it is possible to estimate the threshold velocity for jacket fracture from the images and data in the paper. This analysis reveals a threshold velocity for the RWS 9mm DM11 bullets of 136 m s^{-1} compared with 130 m s^{-1} for Maréchal's work on 9mm FMJ Parabelum bullets. In Thornby's work the gradient increases after the threshold by a factor of 8.5 compared with a factor of 6 for the work by Maréchal. Use of this method may be useful in determining if the steel jackets have different properties and to correlate physical properties, metallurgy and ballistic performance.

2. Experimental procedures

In order to verify, or disprove, the claim that the two sources of 9 x 19mm FMJ DM11A1B2 bullets have a different performance against armour materials, the Metropolitan Police Service (MPS) commissioned a series of performance tests using 9mm DM11A1B2 bullets manufactured by RWS and MEN. Sheffield Hallam University characterised the materials of the bullet construction and along with MPS devised a series of tests building on the approach of Maréchal to try and quantify any difference and determine the cause of any difference in performance and also to correlate any difference with the metallurgy of the bullets.

2.1 Ballistic Performance of two types of 9mm DM11 bullets against soft armour systems

Three soft body armour constructions, namely quilted woven para-aramid, laminated woven para-aramid and ultra-high molecular weight polyethylene (UHMWPE) were tested. These armour schemes were mounted on a flat block of microcrystalline wax (nominal dimensions 420 (H) x 350 (W) x 100 (D) mm). The wax backing provides a semi-rigid backing material on which to mount the armour and it is easily re-melted and reformed post testing.
Critical Perforation Analysis (CPA) is a statistical software tool, developed for the MPS by Cranfield University [5], in order to determine the performance and variability of armour designs. Rounds were fired at a range of velocities (V) until the statistics for CPA were satisfied. V_{mean} and the standard deviation of V_{mean} were determined from between 12 and 21 shots on each amour system.

2.2 Characterization of the Deformation of Bullets under Ballistic Conditions

The two bullet types were fired against free standing targets of 10 and 20 layers of quilted woven para-aramid, typical of the construction used in MPS vests in the last decade. Tests were carried out between 274 m s^{-1} and 321 m s^{-1} for 10 layers and 346 m s^{-1} and 466 m s^{-1} for 20 layers. Free standing targets were used in order to allow high speed video to capture images of perforating bullets to confirm the bullet shape after perforation. The strain rate was not easy to estimate since the armour was free standing and the time for bullet deformation was higher than in the rigidly mounted situation (where it is ~10^4 s^{-1}), an estimate of 10^3 to 10^2 s^{-1} is assumed. Bullets were collected after each test in a wax capture medium, for perforations (P), or from a rubber floor mat in front of the target for non-perforations (NP). Bullets were photographed and measurements carried out on the digital images to determine the deformation criteria C (equation 1). V_{50} for the 10 layer armour was calculated using the arithmetic mean of the 3 fastest non-perforations and 3 slowest perforations. Not enough valid shots were performed to determine V_{50} for 20 layers.

In order to measure the difference in the deformation and jacket fracture behaviour of the two types of bullets the bullets were fired with velocity between 75 m s^{-1} and 198 m s^{-1} at a hard steel plate after the methods of Maréchal and Thornby. The approximate strain rate was 10^4 s^{-1}. The recovered deformed bullets were photographed and measured to determine the deformation criteria, C. They were classified in to three categories; "intact", "fractured jacket" and "fragmented". A plot of the variation of C with velocity was made and linear regression was used to determine the gradient for "intact" and "fractured jacket" bullets. The "fragmented" bullets were excluded. As described by Marchéal [3] the intercept of these two linear regression lines identifies the threshold velocity for jacket fracture for each bullet. The gradient gives the rate of change of deformation with velocity. Comparison of this data for each bullet type can help explain the ballistic performance of the two bullets.

2.3 Deformation of Bullets under Low Velocity - High Load Conditions

In order to try and observe a difference in jacket fracture behaviour between the two types of bullet a low velocity (v~6 m s^{-1}), high load (30 kg) impact test was performed. The test was designed to observe differences in the nature of the fracture of the jacket material without having to resort to ballistic test methods. An Instron drop tower was used to crush a bullet between a fixed and moving steel plate. The energy of the impact was set to that which just initiated fracture in the steel jacket. Three energy levels of 120J (6.3 m s^{-1}), 130J (6.6 m s^{-1}) and 140J (6.8 m s^{-1}) were used to test 3 of each bullet type. The energies are equivalent to 173, 180 and 187 m s^{-1} for an 8g bullet. The approximate strain rate was 4 x10^2 s^{-1}. After the impact test each deformed bullet was examined and measured to determine the extent of the deformation using the deformation criteria C (equation 1) and the number of fractures in the jacket.

2.4 Bullet Characterization

In order to determine if there were any differences in the physical, chemical and metallurgical properties of the RWS and MEN bullets they were removed from the rounds and the weight of 10 bullets of each type was determined using a balance accurate to 0.0001g. The length of each bullet was measured using a vernier calliper accurate to 0.01mm. Handheld XRF equipment was used to measure the elemental composition of the lead core by analysing the lead at the base if each bullet.

Bullets were mounted in a cold set resin and sectioned to approximately half way through their thickness by grinding with silicon carbide abrasive papers. The sections were metallurgically polished to a 1 μm diamond finish. The micro-hardness of the steel jacket was measured on the polished sections along the entire length of the jacket using a Vickers diamond indenter and 100g load (Hv0.1). Indents were spaced about 150 to 200 microns apart.

The chemical composition of the steel jackets was analysed using spark optical emission spectroscopy on a SPECTROMAXx metal analyser (Spectro Analytical Instruments GmbH). The analysis was repeated 3 times for each bullet. Jackets were prepared by removing the lead core and flattening the jacket using a press and light grinding to remove the copper plating. The microstructures of the jackets were observed by optical microscopy and scanning electron microscopy after etching in "2% Nital" (2% nitric acid in ethanol).

3. RESULTS

3.1 Critical Perforation Analysis of the two bullets against various soft armours

The V_{mean} obtained from CPA of each of the armour designs is higher against the RWS 9mm DM11 A1B2 bullet, compared with the same bullet manufactured by MEN. The difference in performance is most apparent in the quilted, woven para-aramid where these results show a difference in V_{mean} of more than ten percent. The lightest systems (UHMWPE) materials appear to be less sensitive to the different bullets.

Table 1: Results from the CPA on 3 types of soft amour using the two types of 9mm DM11 A1B2

Bullet Type / Armour Type (Areal Density)	MEN, V_{mean} [Standard deviation], ($m\ s^{-1}$)	RWS, V_{mean} [Standard deviation] ($m\ s^{-1}$)
Quilted, woven para-aramid, ($5.32 kg/m^2$)	465 [17]	515 [25]
Laminated, woven para-aramid, ($6.30 kg/m^2$)	396 [15]	424 [12]
UHMWPE, ($4.35 kg/m^2$)	507 [27]	513 [8]

3.2 Ballistic Testing Results

3.2.1 Results from Bullets Fired at Woven Para-aramid targets

Ballistic testing of 10 layers of quilted, woven para-aramid resulted in a V_{50} of 282 m s^{-1} for MEN and 300 m s^{-1} for RWS. This suggests that the phenomenon observed in section 3.1 is also being observed in these tests on thinner, free standing armour. High speed video confirmed that the deformations observed were caused by the impact with the armour and not subsequently by contact with the capture medium or range floor. No jacket fractures were observed in this testing due to the armour being free standing with no solid material behind it.

Figure 1 (top row) shows that against 10 layers of quilted woven para-aramid RWS bullets undergo more deformation (higher C value) than MEN bullets in both non-perforation (NP) and perforation (P) cases. Non-perforating RWS bullets have a C value more than 3 times higher that of the MEN bullets. Perforating bullets show less deformation than NP bullets but show a more pronounced difference between RWS and MEN, with a value of C for perforating RWS that is 7 times higher than perforating MEN bullets. Perforating MEN bullets almost maintain their initial shape (very low C).

Against 20 layers (bottom row in **Figure 1**) the situation is different with non-perforating MEN and RWS bullets forming a mushroom shape with the RWS C value being only 18% higher than for MEN. However, for bullets that perforated 20 layers the effect was quite different, with MEN retaining much of its shape and penetrating at 402 m s^{-1} while the RWS bullet mushroomed before penetrating and had to achieve a velocity of 466 m s^{-1} in order to penetrate in this deformed condition. The RWS C value is 270% that of MEN.

Non-Perforating (NP)		Perforating (P)		
MEN 287 m s^{-1}	RWS 292 m s^{-1}	MEN 292 m s^{-1}	RWS 293 m s^{-1}	
				10 layers
NP, C = 0.06	NP, C = 0.2	P, C = 0.01	P, C = 0.07	
MEN 382 m s^{-1}	RWS 399 m s^{-1}	MEN 402 m s^{-1}	RWS 466 m s^{-1}	
				20 layers
NP, C = 0.34	NP, C = 0.40	P, C = 0.10	P, C = 0.27	

Figure 1: Bullets from both perforations (P) and non-perforations (NP). Top row for10 layers and bottom row for 20 layers of woven para-aramid. Velocity is shown above and C below each image.

3.2.2 Results for Bullets Fired at a Hard Steel Plate

The results for the variation of the deformation criteria, C, with velocity when the bullets were fired at a hard steel plate are shown in Figure 2 . Linear regression lines are fitted to the data for "intact jackets" and "fractured jackets", examples of which are given in the accompanying images. The intercept of these two lines gives the threshold velocity of jacket fracture for each bullet type. The gradient of each linear regression (given in the equations on the graph) quantifies the rate of change of deformation with increasing velocity for each type of bullet.

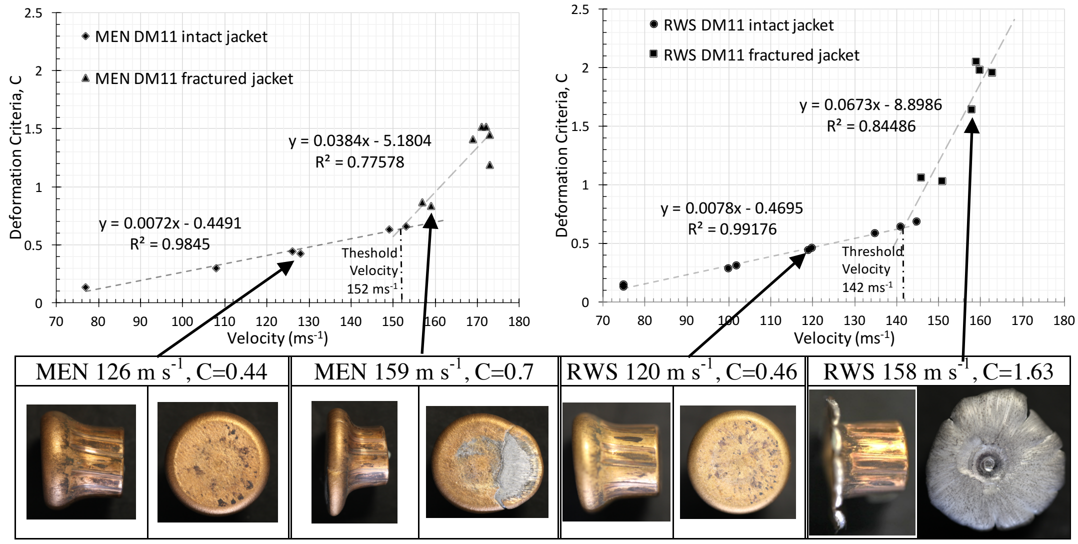

Figure 2: Variation of deformation criteria, C, with velocity after impact with hard steel plate. Images show examples of each bullet type at similar velocities for intact and fractured jackets.

Analysis of the data in
Figure 2 shows that RWS bullets have both a higher level of deformation and a higher rate of increase of deformation with velocity compared to MEN. RWS bullets show a 10% higher C value than MEN bullets at a velocity of 140 m s^{-1}. This suggests the MEN bullet is more resistant to bulk deformation than the RWS bullet. The threshold velocity for jacket fracture is marginally higher for the MEN (152 m s^{-1}) than for RWS (142 m s^{-1}). There is some uncertainty in these figures caused by the larger scatter in the "fractured jacket" data but it can be seen that MEN bullets achieve higher velocities (max. 159 m s^{-1}) without fracturing than the RWS bullets (max. 145 m s^{-1}). Similarly, the lowest velocity for a jacket fracture on MEN bullets was 157 m s^{-1} while for RWS it was 145 m s^{-1}.

3.3 Results from Impact Tests on the Two Bullet Types

Images of typical MEN and RWS bullets after the impact test are shown in **Figure 3**. The images are taken from the tail end of the bullet but inspection for cracks was carried out on both sides. Table 2 and Figure 4 show how the deformation criteria, C, varies with the energy of the impact test for each bullet type. MEN C values are marginally higher (2 to 5%) than RWS C values. There is a linear relationship between energy and the deformation criteria C and the number of fractures. The rate of change of deformation with energy is 15% higher for the RWS bullets than for MEN bullets. **Figure 5** and Table 2 also shows the total number of jacket fractures observed on 3 of each bullet tested at each energy level. RWS rounds are only just beginning to fracture at 120 J where as MEN rounds have a significant number of jacket fractures at the same energy. MEN bullets exhibit a larger number of jacket fractures than RWS at all energies. There is a difference in the rate of increase of fractures with increasing energy (gradient) which is higher for the MEN (0.9 J^{-1}) than for the RWS (0.65 J^{-1}) a difference of almost 40%. The loading in the impact test situation is quite different to the ballistic test, with both front and back of the bullet being compressed and far higher levels of deformation and strain were introduced compared with the ballistic tests.

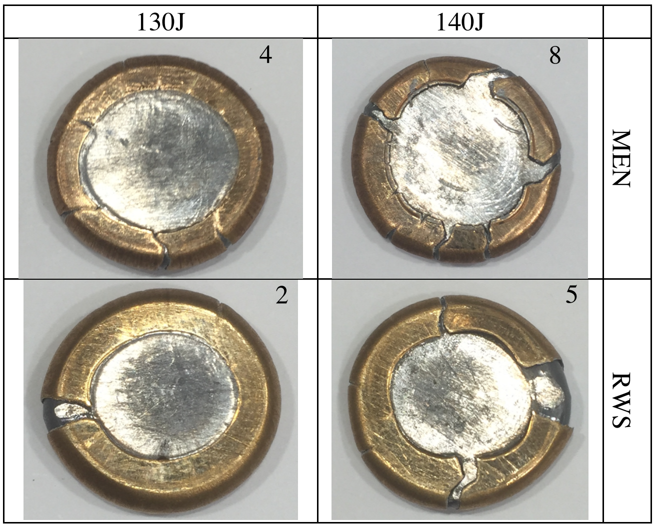

Figure 3: Images of typical bullets (tail end) after impact at 130 J and 140 J in the impact test. Numeral at top right of each image gives fractures observed on each bullet.

Table 2: The data for deformation criteria (C) and total number of jacket fractures from impact testing at 3 energies for the two bullet types

	Deformation Criteria, C		Number of Fractures (total on 3 bullets)	
Impact Test Energy (J)	MEN	RWS	MEN	RWS
120	0.79	0.75	7	1
130	0.85	0.83	16	9
140	0.92	0.91	25	14

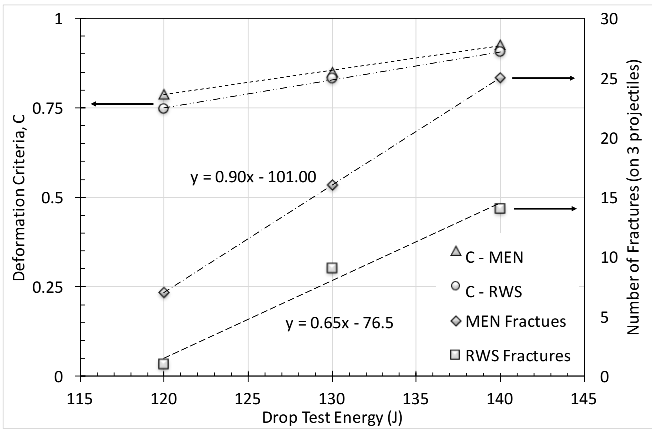

Figure 4: The variation of deformation criteria, C (left hand y-axis) and the total number of fractures on 3 bullets (right hand y-axis) with energy in the impact test.

3.4 Bullet Properties

The results from the weight and length measurements of 10 bullets of each type are shown in **Table 3**. There was no significant difference between the two bullet types in terms of weight or size or variation thereof. The XRF analysis of the lead core, as measured on the base of the bullet, is shown in Table 4. The results show a close similarity between the two lead cores which appear to be made from a lead with 2.5% antimony. The other elements detected could either be present in the lead or more likely are detected due to the nearby presence of the copper plated steel jacket, particularly the Fe, Cu and Zn.

The chemical composition of the steel jackets along with the closest matching standard AISI SAE grades are given in **Table 5**. It can be seen that the MEN and RWS closely match with the AISI SAE 10xx series of plain carbon, non-resulphurised steels with Mn maximum of 1.00 [6, 7]. However, the two steels are different, primarily in terms of the carbon content, with the MEN jacket having a significantly higher carbon content ($C_{mass\%}$ = 0.11wt% +/- 0.03) compared to the RWS jacket

($C_{mass\%}$ = 0.07 wt% +/- 0.01). Other differences are seen in the Mo, Ni and Al content. The published range of mechanical properties of the closest AISI steel grades are given in **Table 6** [8]

The micro-hardness results on the cross-section of the bullet steel jackets are shown in **Figure 5**. The bullet tip region is shown in the dashed line box. In this region, the average micro-hardness of the MEN steel jacket was Hv0.1 = 156 +/- 6 and the micro-hardness of the RWS steel jacket was Hv0.1 = 159 +/- 5. (+/- standard deviation). By comparison the hardness of the side wall for both bullet types was higher, with MEN side wall Hv0.1 = 182 +/- 4 and RWS side wall Hv0.1 = 188 +/- 10. Compared with the values given in **Table 6** the jacket hardness is significantly higher than the values for cold drawn bar, where the maximum hardness is given as HB=105 (approximately equivalent to Hv=113). This suggests that significant cold work has been done on the jacket to create this higher hardness and accompanying higher strength.

The optical and scanning electron microscope (SEM) images from the sectioned bullets are shown in **Figure 6** and **Figure 7** respectively. The microstructures of the jackets at the tip and the side wall show that the two steel jackets have significantly different microstructures. The MEN bullet jackets have equi-axed ferrite grains of about 20-50 µm in size, with isolated regions of pearlite and little difference between the tip and side wall structure. In the RWS bullets jackets, the grains are smaller, and are moderately elongated at the tip, but substantially elongated in the side wall. There are small precipitates, which are probably carbides, but no detectable pearlite. The significant differences between these two steel microstructures are a result of both the different chemistry and different thermo-mechanical processing histories.

Table 3: Weights and lengths of 10 DM11 bullets from each of the two manufacturers

	Weight (g)		Length (mm)	
	MEN DM11	RWS DM11	MEN DM11	RWS DM11
Average	8.011	8.012	15.55	15.61
Std Dev	0.006	0.007	0.030	0.029

Table 4: XRF analysis of the lead core within the two bullet types.

	Element (Mass %)								
Bullet Type	Pb	Sb	Si	P	Cu	Fe	Ni	Zn	Other
MEN	93.52	2.53	1.99	0.706	0.396	0.196	0.142	0.034	0.49
RWS	93.7	2.45	2.11	0.74	0.522	0.289	0.114	0.049	0.03

Table 5: The chemical analysis of the steel jacket from each bullet type (balance Fe) compared with closest match SAE AISI grades

	Element (wt%)								
Bullet//Grade	C	Si	Mn	P	S	Cr	Mo	Ni	Al
MEN	0.108	0.033	0.243	0.008	0.009	0.03	0.011	0.047	0.066
RWS	0.071	0.038	0.223	0.015	0.006	0.023	-	0.02	0.046
SAE 1006	0.08 max	-	0.25-0.4	0.04	0.05	-	-	-	-
SAE 1008	0.1 max	-	0.25-0.4	0.04	0.05	-	-	-	-
SAE 1010	0.08-0.13	-	0.3-0.6	0.04	0.05	-	-	-	-

Table 6: Properties of SAE AISI 1006, 1008 and 1010 in bar form and different conditions [8]

Steel	Condition	Tensile (MPa)	Yield (MPa)	Elongation (%)	Reduction in Area (%)	Hardness (HB)
1006	Hot Rolled/Cold Drawn	295/330	165/285	30/20	55/45	86/95
1008	Hot Rolled/Cold Drawn	305/340	170/285	30/20	55/45	86/95
1010	Hot Rolled/Cold Drawn	325/365	180/305	28/20	50/40	95/105

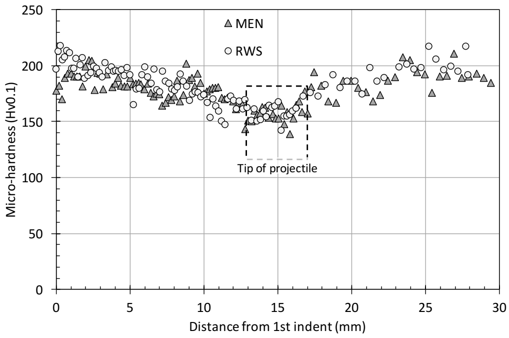

Figure 5: Micro-hardness (Hv0.1) of the steel jackets (tail to tail). Dashed line box indicates tip region. Side wall hardness is average at 4.5mm to 6.5mm

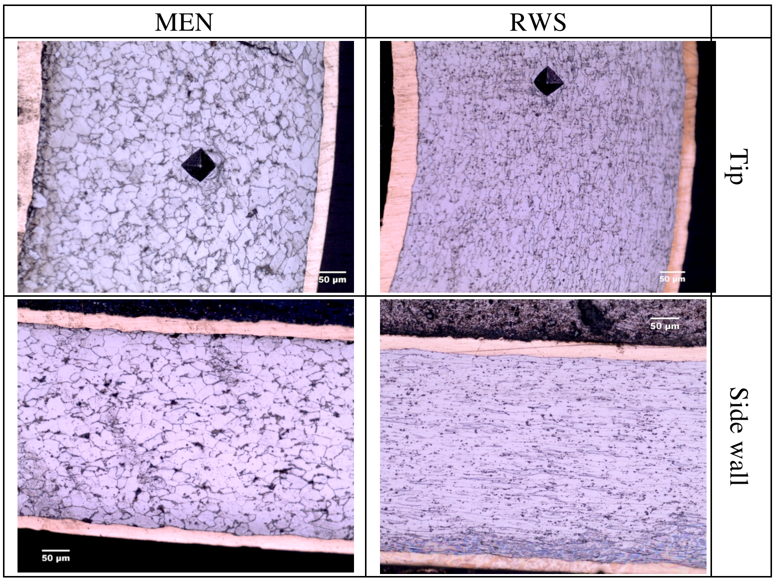

Figure 6: Optical images of the microstructure of the steel jackets on the MEN and RWS bullets.

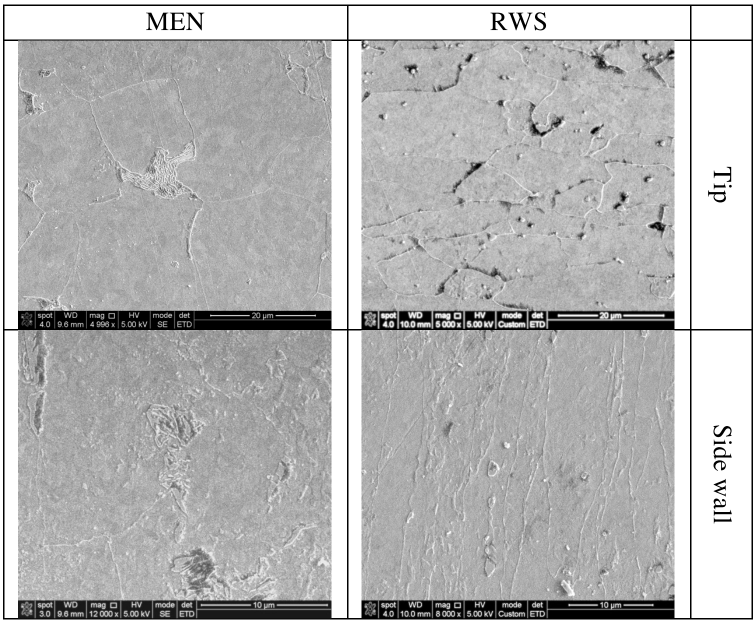

Figure 7: SEM images of the microstructure of the tip and side wall of both bullets

4. Discussion

The ballistic results clearly confirm that there is a measureable difference in the ballistic performance of the two type of 9mm FMJ DM11 A1B2 bullets. The difference is most obvious in the CPA V_{mean} results for soft armours made from quilted, woven para-aramids with $\Delta V_{mean} = 50$ m s^{-1} (11%). The result shows that MEN bullets are more effective penetrators than RWS bullets. This effect is replicated in tests on 10 layers woven para-aramids where, at lower velocities, a 6% difference was observed in the V_{50}, with MEN again found to penetrate more readily than RWS.

Observations and measurements on both perforating and non-perforating bullets fired against free standing woven para-aramid armours clearly shows a difference in the deformation undergone by MEN and RWS bullets. It is very clear that MEN bullets are less deformed than RWS bullets in all cases. The largest difference was observed for perforating rounds, where MEN retain most of their original shape while RWS are significantly deformed. At lower velocities perforating MEN bullets appear to have undergone very little deformation, whereas RWS bullets have a distinctive rounded nose. It appears that whether a bullet perforates or is stopped depends upon how much it is deformed in the very early stages of contact with the armour. A bullet which is able to retain its original shape for longer will result in a higher energy density at the contact point for longer, and this may be sufficient for the bullet to begin to defeat the quilted woven para-aramid structure. A bullet such as the RWS, which is more heavily deformed in the initial stages of contact, will require more energy to penetrate since the force is spread over a larger area by the deformed bullet tip. An example is given in **Figure 1** where MEN perforates at 406 m s^{-1} with a low level of deformation where the deformed RWS bullet required a velocity of 466 m s^{-1} to perforate.

When the bullets were fired against a hard steel plates MEN bullets underwent slightly less deformation than RWS bullets (10% less at 140 m s^{-1}) and the rate of increase of deformation with velocity was greater for RWS than for MEN bullets by about 8%. The threshold velocity for jacket fracture was 7% higher for MEN than for RWS, although some uncertainty exists in this figures due to the scatter in the data for the fractured jackets.

Observations of the differences between the MEN and RWS bullets using a drop test also showed significant differences. The MEN and RWS bullets had very similar levels of deformation. The on-set of fracture appeared to occur at lower energies for MEN and there were many more fractures in MEN jackets at the same deformation levels. The rate of increase of fractures was higher for MEN than for RWS. This suggests that MEN bullets have a lower elongation to failure and are less ductile and more prone to fracture at the same strain than RWS bullets.

In the ballistic testing carried out here the fracture of jackets was not observed. However, the fracture of the bullet jacket may become a factor of interest with higher velocities, when the armour is more rigid (e.g. consolidated UHMWPE) or when tested with a more rigid backing, where fracture of jacketed bullets is more readily observed. Thus, the ability to measure the threshold of jacket fracture at ballistic strain rates, as demonstrated here, may be of interest when considering armour systems being tested on rigid or semi-rigid backings against high velocity rounds.

In terms of chemical composition of the steel jackets, the differences lie mainly in the carbon content, with MEN jackets being made from a higher carbon content steel than the RWS bullets. Higher carbon steel generally has higher strength and lower ductility. Lower ductility results in lower elongation at break in quasi-static mechanical tests. However, the thermo-mechanical processing history of steels also has a significant effect on the quasi-static mechanical properties as shown in **Table 6**, where the differences between a hot rolled and a cold drawn material are of the same order as, or greater than, the differences between grades with different carbon contents. Different thermo-mechanical processes result in different steel microstructures and it appears that the difference between MEN and RWS steel jacket microstructures is a result of such differences in processing (see **Figure 6** and **Figure 7**). The sheet which was used to make MEN jackets has at some stage been heat treated to recrystallize and grow the grains and remove the preferred orientation (texture) which would have been present from the sheet rolling process. This would have made it easier to work in the bullet making process, especially in swaging or deep drawing. The cold work which has then been done to form the MEN bullet has not resulted in a significant elongation of the grains on the side wall despite a reduction in thickness of around 50% at the side wall. The RWS steel jackets show a moderately elongated and finer grain microstructure at the tip but significantly elongated gains at the side wall. This suggests that the sheet was originally in a different condition before bullet manufacturing started, with more of the sheet rolling texture still present. The bullet manufacturing process for RWS has resulted in a greater texturing of the microstructure at the sidewall. This is suggestive of different manufacturing processes being used for MEN and RWS bullets with more severe cold work taking place on the RWS materials. The end result of the combination of steel chemistry and thermo-mechanical processing is that both steel jackets have a very similar hardness (which can be used to estimate strength). However, the ductility of the two steel jackets could be quite different due to the difference in the carbon content, thermo-mechanical processing and resultant microstructures. From the deformations observed in the ballistic tests it seems that initial deformation of the bullet is significant in determining the effectiveness of the bullet in penetrating quilted woven para-aramids and it is apparent that MEN steel jackets which show evidence for lower ductility, deform less and as a result they more readily penetrate some armour structures. Where a higher ductility steel jacket is present (RWS) the nose of the bullet was observed to more easily deformed in the early stages of contact and this reduces its ability to penetrate due to the reduction in the energy density as the nose of the bullet spreads.

5. Conclusions

- The MEN and RWS bullets jackets show a small but significant difference in ballistic performance against woven para-aramid armour structures with MEN being a more threatening bullet
- MEN bullets were observed to undergo less deformation than the RWS bullets in ballistic tests against para-aramids and a hard steel plate. In impact testing MEN bullet jackets were observed to be less ductile than RWS rounds and suffer more fractures than RWS at the same strains. This lower ductility and higher resistance to deformation results in the MEN bullet maintaining its original shape during very early stages of impact a better than the RWS bullet. This may explain the MEN bullet's ability to penetrate woven para-aramid armours at lower velocities than the RWS bullets.
- Differences in the composition of the steel jackets on the two bullets were observed with the MEN jacket being a higher carbon grade than the RWS jacket. The micro-hardness of the two steel jackets appeared very similar and as a result it can be inferred that the strength of the two steels is the same.
- However, the microstructures of the two jackets were significantly different, which has resulted from (i) the different carbon contents and (ii) from differences in the thermo-mechanical processing that the steel sheets received before and during being shaped in to a bullet jacket.
- A combination of the chemical and microstructural differences has resulted in steel jackets which have quite different deformation behaviour. The MEN jacket appears to have lower ductility and lower elongation to break with the lower ductility resulting in the ability to retain more of the original shape when impacting soft armour systems
- In these tests, no jacket fractures were observed but at higher velocities, and when using more rigid armour or backings, the fracture of the jacket and the subsequent effects on armour performance would be of interest. The methods set out here for determining the jacket fracture behaviour of bullets of different forms, such as for example AK47 lead core rounds from different countries, would be of interest to the armour designer and end user.

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