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Material characterization of a novel new armour steel

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Abstract. The material characterization of a novel new armour steel with comparison to a leading commercial benchmark alloy is presented. Direct ballistic and experimental comparison is drawn. The 5.56 × 45 mm [M193] and 7.62 × 51 mm [NATO Ball] projectiles were used in a cartridge type high pressure barrel configuration to evaluate the superior plugging resistance of the new steel over a range of plate thicknesses. To characterize the dynamic plasticity of the materials, quasi-static, notched and high temperature tensile tests as well as Split Hopkinson Pressure Bar tests in tension and compression were performed. The open source explicit solver, IMPACT (sourceforge.net) is used in an ongoing numerical and sensitivity analysis of ballistic impact. A simultaneous multi variable fitting algorithm is planned to evaluate several selected numerical material models and show their relative correlation to experimental data. This study as well as micro-metallurgical investigation of adiabatic shear bands and localized deformation zones should result in new insights in to the underlying metallurgical and physical behavior of armour plate steels during ballistic perforation.

1 Introduction

This paper forms part of an ongoing investigation into the armour material design and optimization for level 1 kinetic energy threat [1]. The 5.56 × 45 mm M193 projectile is the limiting caliber for this level and the typical target perforation mechanism is plugging (figure 1) with adiabatic shear bands as well as intergranular cracks (figure 2). At present commercial armour plate data sheets only focus on the following mechanical properties; hardness, yield strength, tensile strength, minimum elongation and low temperature impact toughness. The hardness of the material is often included in the commercial product name and seems to be the only required mechanical property distinguishing ballistic resistant plate from structural steel. Hardness is an indicator of tensile strength and as extensive analytical work [2–5] relies almost entirely on the tensile strength of the material, the use of material hardness as a ballistic performance indicator is entirely valid in certain cases. Recent work [6] indicates, however that material hardness alone might not be the only required mechanical property for optimal ballistic performance. The development of Dual-Phase, TRIP and especially TWIP alloys [7] (with tensile strength of ≈1700MPa at 45% strain), indicates that enhanced plastic energy absorption could be attained with higher work-hardening rates. Thermal softening delays, dynamic plasticy damage and phase transformations should also be included in the development of optimal ballistic performance. The new experimental alloy was developed as part of a group of alloys, aimed at providing superior ballistic resistance for small-arms projectiles at lower plate thickness levels, primarily for use in light armoured vehicles. The chemical composition of the alloys was based on high manganese content, as well as moderate levels of chromium, nickel and molybdenum. In the as-rolled condition, the plate produced to these alloy formulations produced a predominantly martensitic microstructure, with some retained austenite evident. Alloy 1 was the alloy in the group aimed at the semi-structural 500 HB application, where the armour plate is fabricated into the vehicle chassis and where the 7–8 mm armour plate would provides adequate resistance to the NATO STANAG 4569 Level 1 ballistic threat [1]. This experimental ballistic resistive material Alloy1 [8], a tempered variant Alloy1 T200 and a leading commercial ballistic benchmark material have been tested. The normal tensile tests, high temperature tensile tests, notched tensile tests and high strain-rate SHPB tests results are summarized with the ballistic test procedure and results discussed in detail.

2 Ballistic performance test procedure and results

2.1 Test equipment and procedure

A high pressure ballistic test barrel (figure 3) with standard cartridge charge was used in this investigation. Each cartridge is loaded before the shot to control the impact velocity, however the range of impact velocity for a single charge can be as high as 50 m/s (figure 4). The ballistic test procedure and evaluation rules defined in [9] were used as the starting point and only slight deviations are allowed to reduce cost and testing time. A standard witness system consisting of a 0.5 mm aluminium plate positioned 150 mm from the back face of the test plate would typically be used. This witness plate should extend over a large enough area to detect all of the projectiles and fragments. Characterization of impact events near the ballistic limit of the material is defined as partial penetration if light is not observed to pass through the witness plate or complete penetration if the light passes through the witness plate. For this investigation a simplified and more conservative approach was followed by visual inspection of the test plate's back face. An impact event above the ballistic limit results in a clear hole through the plate and is classified a complete perforation or CP. With the impact velocity well below the ballistic limit almost no damage is observed on

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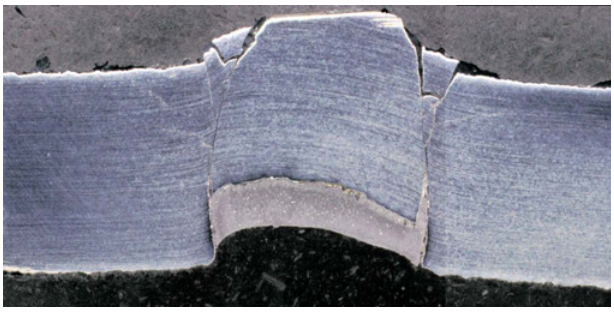

Fig. 1. Micrograph of ballistic plug formation and partial expulsion on the newly developed armour steel (5.56 × 45 mm on 7.5 mm plate).

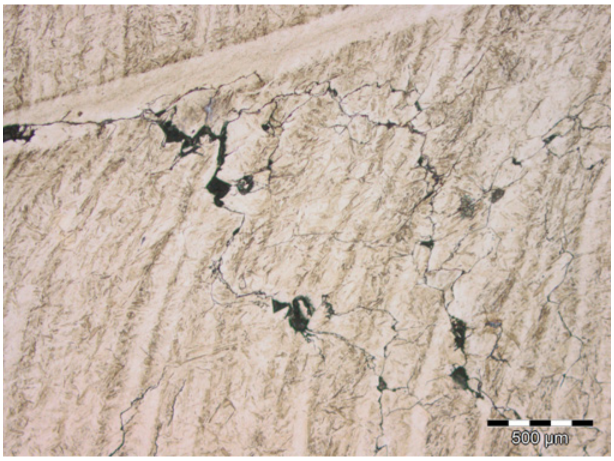

Fig. 2. High magnification of micrograph in figure 1 (area close to partial plug formation).

Fig. 3. High pressure ballistic test barrel.

the back face of the test plate with only slight bulging in some instances. These types of impacts are classified as non-perforation or NP. Impact events near the ballistic limit of the plate result in partial perforations or PP as seen in figure 5. Circumferential cracks with an inclosed angle larger than 180° are classified as complete perforations. The following procedure was followed for every test plate. Firstly a few shots are used to establish a test range with at least one CP and one NP. Once the test range is known, the charge is varied only slightly to influence the impact velocity. The aim of this section of the test is to vary the impact velocity required by the test plate such that half of the shots result in NP and the other half in CP. All shots should also have in impact velocity within 40 m/s of each other. This process has proved to

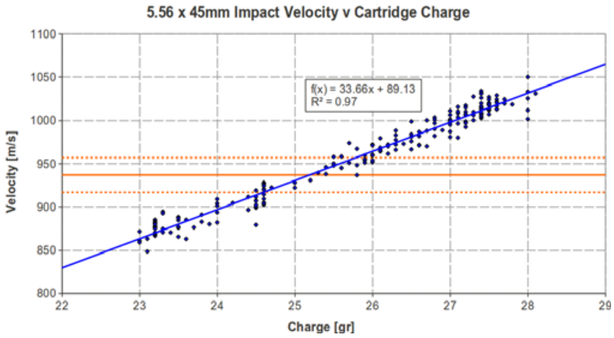

Fig. 4. Impact velocity range of cartridge type high pressure ballistic test barrel configuration.

Fig. 5. Classification of partial perforation for impacts near the ballistic limit of the material.

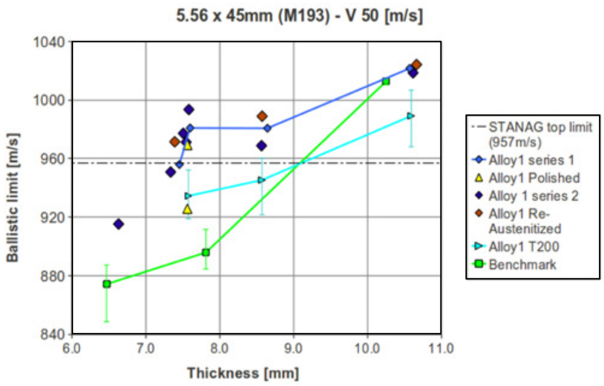

Fig. 6. Ballistic performance of Alloy1, Alloy1 T200 and the Benchmark material against 5.56 × 45 mm (M193) projectile at 10 m.

be challenging for some tests and a reduced number of shots had to be used to calculate the V50 ballistic limit (50% probability of perforation) value. During the test the following values were recorded, Shot number (also marked on the plate.), Cartridge charge [grain], Muzzle velocity [m/s] and Impact result [CP, PP or NP]. After the test all PP impact events are closely examined to verify if any fragments were ejected. Impact events with fragments are re-classified as CP and impact events without fragments as NP. The muzzle velocity is adjusted to the impact velocity value by subtracting velocity drop over 13.5 m (1.23 $\frac{m/s}{m}$ for 5.56 × 45 mm). The average is calculated using an equal number of CP and NP events with the fastest NP values and slowest CP values included.

2.2 Ballistic results for 5.56 × 45 mm (M193) projectile

A total number of 22 plates were tested with the 5.56 × 45 mm M193 caliber round. The results are presented in figure 6 with the upper STANAG limit (Table 1) in dotted

Table 1. Kinetic energy threat classification [1].

Level	KE Threat		
	Ammunitions	Supplier / Specific test ammunitions	V proof [m/s] {± 20 m/s}
1	7.62 mm x 51 NATO ball	Ball M80, copper jacket, 9.65 g lead core or C21, 9.5 g, DM41 with tomac jacket and lead core, projectile weight: 9.45 g	833
	5.56 mm x 45 NATO SS109	SS109, 4.0 g, M855, DM11, tomac jacket, steel and lead core, projectile weigth: 4 g	900
	5.56 mm x 45 M193	M 193, Ball 3.56 g	937

Table 2. Summary of ballistic results for 5.56 × 45 mm (M193) projectile.

Plate no.	Thickness [mm]	V50 [m/s]	+	-	No. Shots
TFL 1/3 [2210124] TP1	7.454	955.96	17.93	17.91	18
TFL 3/1 [2210124] TP2	7.599	980.88	14.21	9.74	10
TFL 5/1 [2208934] TP3	8.647	980.72	19.97	15.88	18
TFL 3/2 [2210125] TP4	10.574	1021.62	6.72	19.21	10
Alloy #1 T SM12 TP22	7.577	934.50	17.70	15.57	22
Alloy #1 T SM10 TP25	8.574	945.33	15.01	23.59	22
Alloy #1 T SM1 TP26	10.595	989.17	17.62	21.14	20
Alloy #1 SM12 TP33	6.631	915.33	15.48	20.53	18
Alloy #1 SM11 TP39	7.336	950.83	22.28	17.67	16
Alloy #1 SM15 TP29	7.546	971.24	18.66	9.84	18
Alloy #1 SM12 TP30	7.582	993.49	18.11	9.09	20
Alloy #1 SM13 TP31	7.507	977.26	15.34	21.00	20
Alloy #1 SM7 TP40	8.567	968.82	22.58	14.92	20
Alloy #1 SM3 TP32	10.620	1018.58	18.51	17.59	18
Alloy #1 RA900 SM12 TP34	7.392	971.46	11.34	9.97	18
Alloy #1 RA900 SM7 TP35	8.575	988.92	21.58	13.26	22
Alloy #1 RA900 SM3 TP36	10.667	1024.19	18.41	14.29	24
SM12 TP37 Back Polished	7.563	969.57	14.82	18.12	12
SM12 TP37 Front Polished	7.563	925.70	13.35	14.41	6
Benchmark TP16	6.468	874.27	13.04	25.75	22
Benchmark PT12	7.813	895.86	15.79	11.23	12
Benchmark PT13	10.253	1012.66	2.24	2.26	8

lines and listed in Table 2. The data range bars have been removed from Alloy1 data points to clarify the result in figure 6. Alloy1 is positioned above both the benchmark and Alloy1 T200. The top limit of $937 + 20 = 957\,\mathrm{m/s}$ for 5.56×45 mm (M193) projectile at 10 m [1] is shown by the dotted line which can be used to determine the minimum required thickness to defeat the 5.56×45 mm (M193) projectile. A plate thickness of 9 mm is required by both the benchmark and Alloy1 T200 materials with only 7.3 mm (lower bound value) required by Alloy1. Series 2 of Alloy1 show the variance between different plates from the same cast and heat treatment. The re-austenitized plates proved that no substantial auto-tempering should be allowed after the final rolling of the plates as ballistic preformance was similar to series 1 of Alloy1. One curious result is the ballistic performance effect of a polished (surface ground by hand with soft abrasive) surface finish in the front side of the plate (Yellow triangles). A reduction in ballistic limit of 44 m/s is seen with the front face polished compared to the back face. The ballistic limit of the plate with the back face polished is similar to plates without any polished faces.

3 Split Hopkinson pressure bar results

Elastic stress waves measured in the pressure bars are related to force and displacement values within to the specimen as shown in the next section. The dynamic plasticity response of the material is then calculated [10,11].

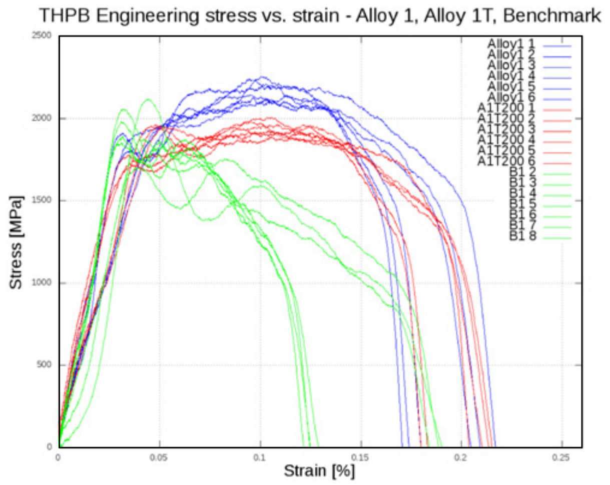

Fig. 7. THPB Stress Result Summary of Alloy1, Alloy1 T200 and the Benchmark alloy.

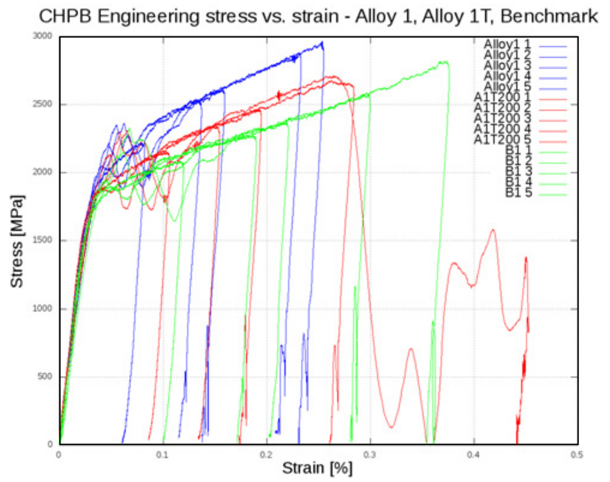

Fig. 8. CHPB Stress Result Summary of Alloy1, Alloy1 T200 and the Benchmark alloy.

3.1 Tensile results

The energy absorption capacity in tension, as well as an apparent delay in localized deformation of the experimental Alloy1 when compared to the benchmark alloy, seems higher within the strain-rate range of 500–1200$\frac{1}{s}$.

3.2 Compression results

A clear trend is seen in figure 8 with Alloy1 above Alloy1 T200 and the benchmark material below both. The energy absorption capacity in compression, as well as the work-hardening rate of the experimental Alloy1 seems higher within the strain-rate range of 300–1000$\frac{1}{s}$.

4 Conventional tensile tests

Some of the completed tensile test results are reported in this section for direct comparison of the materials.

Table 3. Conventional tensile result summary from 35 tenisle tests of Alloy1.

Value	UTS [MPa]	Elongation [%]
Minimum	1954.59	4.06
Maximum	2416.40	17.77
Mean	2104.95	13.58
Stdev.	72.13	3.20

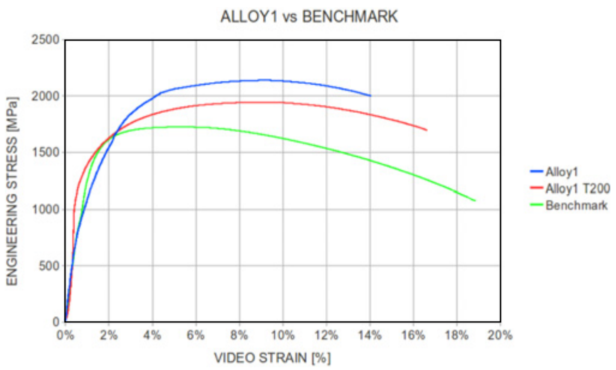

Fig. 9. Conventional tensile result comparison for Alloy1, Alloy1 T200 and the Benchmark alloy.

4.1 Normal tensile tests

A number of standard tensile tests were performed on Alloy1 using EDM profiled and face ground specimens, yielding geometric accuracy of 0.010 mm on the width and 0.050 mm on the thickness. The results are summarized in the table 3. A comparison of the standard tensile behavior, tested on a machine with video extensometer, of Alloy1, Alloy1 T200 and the Benchmark alloy is shown in figure 9. The energy absorption capacity of the materials is not evident but nevertheless, direct comparison shows the experimental Alloy1 has a higher tensile strength with Alloy1 T200 lower and the benchmark material the lowest. The delay in localized deformation for Alloy1 is also evident.

4.2 Notch tensile tests

Some of the notched tensile specimens were tested without the video extensometer and the direct comparison with therefore is not possible at this stage. Only results for the Alloy1 T200 and benchmark materials are therefore shown. The stress triaxiality effect on the fracture strain can be compared using the video strain in figure 10. Alloy1 T200 failed at lower strain for each of the notch factors and is clearly more severely affected by triaxiality than the benchmark material.

4.3 High temperature tests

Only Alloy1 and the benchmark steel were tested at elevated temperatures as heating of the specimen past 200°C would negate any prior tempering effects. The comparative results in figure 11 show a clear delay in thermal softening of Alloy1 up to 500°C if compared to the benchmark alloy. After this point the tensile strength of the two materials converge.

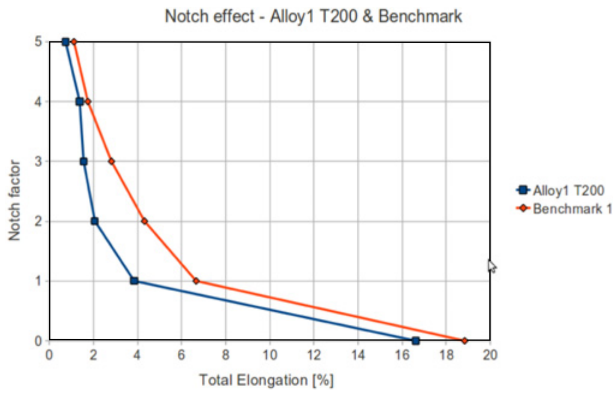

Fig. 10. Comparison of the notch effect on Alloy1 and the Benchmark alloy.

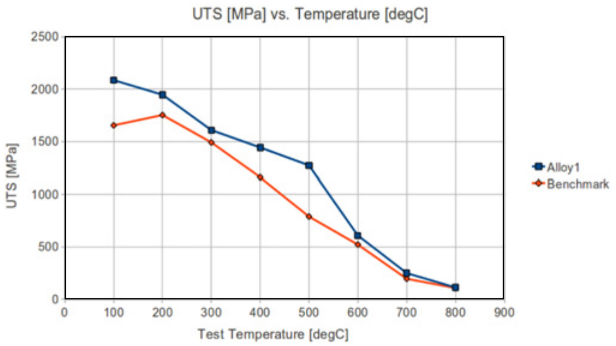

Fig. 11. High temperature tensile result for the Alloy1 and Benchmark materials.

5 Summary and conclusions

Some results on an experimental, ballistic and numerical characterization of a novel new armour steel with comparison to a current commercial benchmark alloy, is presented. A new experimental Alloy1 [8], a tempered variant Alloy1 T200 (200°C for 1h) and a commercial ballistic benchmark material were tested. The ballistic test indicates that Alloy1 requires a minimum thickness of 7.5mm, while both the tempered variant and the benchmark steel seem to require 9 mm for STANAG Level 1 6. SHPB tests show an apparent higher energy absorption capacity of Alloy1 at strain-rates of 500–1000 1/s. Conventional tensile tests reveal the higher tensile strength of Alloy1 compared to Alloy1T200 and the benchmark alloy. Alloy1 T200 is more severely affected by triaxiality than the benchmark material, as shown in the notched tensile tests (results from Alloy1 could not be compared at this time). High temperature tensile tests show a clear delay in thermal softening of Alloy1 up to 500°C if compared to the benchmark alloy.

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