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Dynamic testing and simulation of 9 mm full metal jacket ammunition

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Abstract. Ballistic protection for armed forces requires a continuous performance improvement to successfully face ever evolving threats and scenarios. Ballistic tests are conventionally carried out in order to assess and validate the levels of protection to a high degree of accuracy. Although very effective, those tests are often time consuming and lack the necessary flexibility. A better approach would be to set up a numerical protocol for a number of simulations and only carry out final real life validation tests. Unquestionably, the main advantage of finite element modelling is the possibility to simultaneously evaluate a wide variety of configurations and their interactions (materials, geometry, architecture, etc.). For reliability, it is necessary to use sufficiently precise material behaviour models to accurately transcribe the phenomena observed during the impact. Our study focuses on the mechanical behaviour of 9 mm ammunition materials, namely a lead alloy core and a steel alloy jacket. For this purpose, a preliminary study (not presented here), was carried out on both the lead core and the steel jacket separately and the parameters for each constitutive model were determined. Lead-steel cylindrical samples, extracted from the ammunition, have been used for the validation of the entire constitutive model. By utilizing those samples, a high degree of the ammunitions material properties have been retained. SHPB tests have been carried out in multiple conditions, varying the striker speeds and temperatures. Additionally, the tests were recorded with an ultra-high speed camera. Strain gages were used to record signals along the input and output bars. Those measurements have been compared to numerical results using Finite Element code (ABAQUS® Explicit). A very satisfying correlation between the experimental data and the simulation has been reached, thus validating the jacket and core constitutive models and interactions for subsequent studies of ballistic impacts.

1 Introduction

The assessment and validation of protection system is conventionally carry out in ballistic tests. Although very effective, those tests are often time consuming and lack the necessary flexibility, but incorporating them in final real life validation tests is still invaluable. Nevertheless, setting up numerical protocols for a large number of simulations is a better and more cost effective approach to this problem. Unquestionably, the main advantage of finite element modelling is the possibility to simultaneously evaluate a wide variety of configurations and their interactions (materials, geometry, architecture, etc.). For reliability, it is necessary to use sufficiently precise material behaviour models to accurately transcribe the phenomena observed during the impact [1-2-3]. Our study focuses on a small calibre ammunition, with a ductile core, impacting composite body armours [1-4]. The ammunition is composed of a lead alloy core and a steel alloy jacket. Usually, those materials are studied in classical compression and tensile tests using raw surrogate material, due to the difficulty

to machine samples [3-5]. This makes it possible to adjust suitable constitutive and failure models for the different materials. However this method has some limitations. By neglecting the geometry of the ammunition, which has undergone multiple stages of forming, behavioural differences are induced and can result in an incorrect modelling.
In the preceding study, the mechanical behaviour of the lead alloy core has been examined in order to identify a constitutive model [6-7]. Concurrently, the steel jacket material surrounding the lead core has also been investigated, leading to the identification of the Johnson-Cook model parameters [8].
This paper focuses on the mechanical behaviour of the core-jacket assembly at high strain rates under compression loading. By testing the assembly as a whole, crucial material interaction are also studied. Lead-steel cylindrical samples extracted from the ammunition have thus been utilized for the validation of the entire constitutive model. SHPB tests have been carried out in different conditions, varying striker speeds and temperatures, in order to verify if strain rate and temperature sensitivities are correctly taken into account in both material models. Material interactions have also been considered in the model. The resulting signals and deformation faces have been compared to numerical results using Finite Element code (ABAQUS® Explicit).

2 Sample preparation

The studied 9 mm ammunition is composed of a lead alloy core and a steel alloy jacket (Fig 1.a). The goal of this study is to characterize the mechanical behaviour of such ammunition in conditions close to real bullet impacts. This is why the geometry of the samples is kept as close as possible to the geometry of the ammunition (see Fig 1.b and c). It is composed of the same lead core studied in [6] and the steel jacket, studied separately in an internal project. The dimensions of the final sample are 9.0 mm in diameter and 5.7 mm height. The characteristic backside of the ammunition, visible on the left of the schematic depiction in Fig 1.c), is kept unchanged.

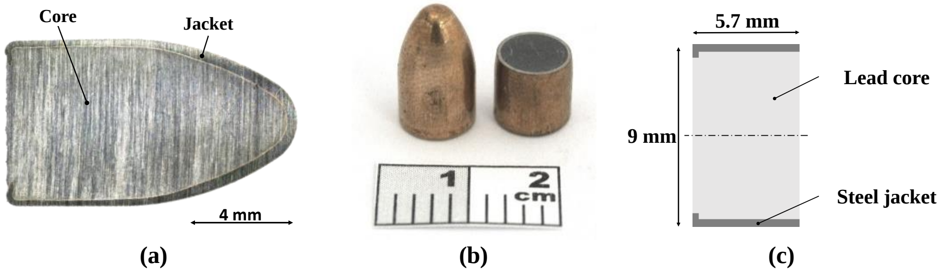


Fig 1. (a) Longitudinal section of the ammunition, **(b)** ammunition and sample obtained after machining, (c) schematic depiction of the sample.

3 Dynamic experimental study of the core – jacket assembly

3.1 Experimental protocol

The study of the dynamic mechanical behaviour of the core - jacket assembly is carried out using a Split Hopkinson Pressure Bar (SHPB) setup. The setup is composed of a steel striker with a diameter of 20 mm and a length of 600 mm. The steel input bar has a diameter of 20.5 mm and a length of 1900 mm while the aluminium output bar has a diameter of 20 mm and a length of 1900 mm. Strain gauges in a full-bridge configuration glued onto the surface of the bars enable the measurement of the generated signals. A sacrificial plate composed of the same material as the output bar is positioned between the sample and the output bar to prevent indentation of the bar. Petroleum jelly is used as lubricant for room temperature test, whereas copper grease is used for tests at elevated temperature. A resistive furnace, similar to the one in [9], is used for the high temperature tests. A thermocouple is placed on the surface of the sample to measure the temperature of the specimen. During the test, the samples are observed using a Shimadzu HPV-X ultra-high speed video camera coupled with LED backlighting.

In order to study the strain rate and temperature sensitivities, tests with different loading conditions are carried out. The strain rate sensitivity is evaluated at room temperature using different initial striker velocities (v_1 = 6 m/s, v_2 = 11 m/s and v_3 = 13.2 m/s). Likewise, the temperature dependency is assessed by varying the temperature at a constant striker speed of 11 m/s (T_1 = 293 K, T_2 = 373 K and T_3 = 473 K). Tests in each of those six conditions are repeated three times to also evaluate the repeatability.

3.2 Experimental results

The accuracy of the experimental tests and their results is critical for any research task. It is commonly verified by conducting the test multiple times in identical conditions. For this purpose, the different signals measured using the strain gauges on the input and output bars are converted into deformations and compared in Fig 2.
The signal comparison shows a high degree of overlapping for the amplitudes, whether on the input or output bar. This indicates a satisfactory level of accuracy for the tests.

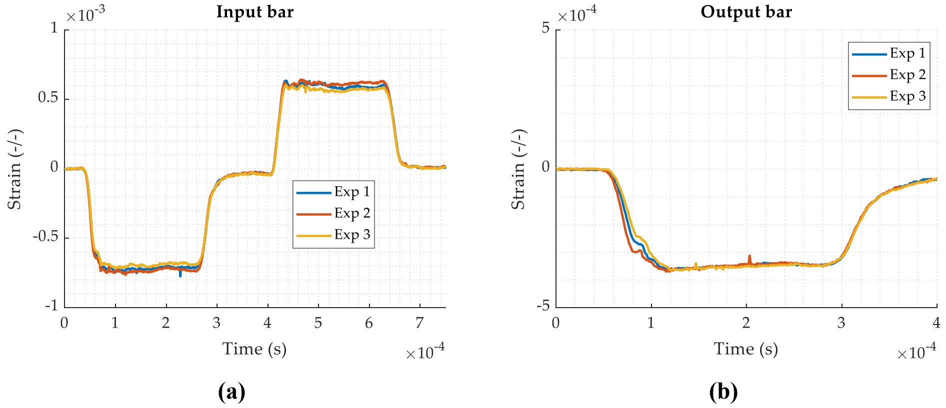
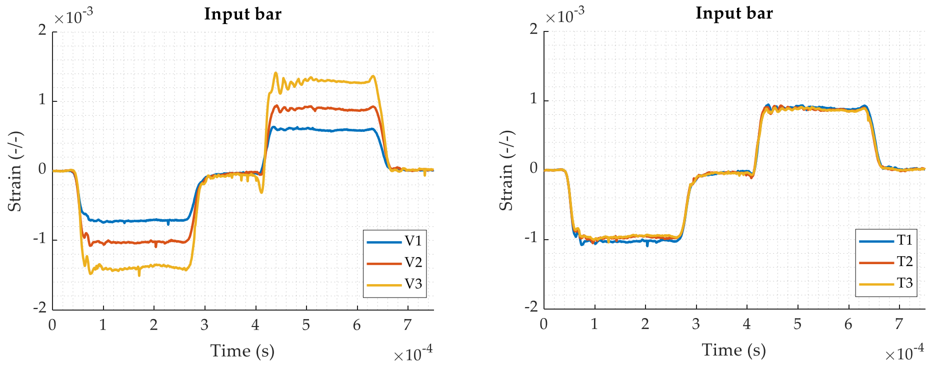


Fig 2. Comparison of the strain signals for the 3 tests at v_1 = 11 m/s and 293 K measured on: **(a)** the input bar; **(b)** the output bar.

It is possible to investigate the dependencies on the strain rate as well as on the temperature by comparing the measured strains.
On the input bar (Fig 3.a), we can verify that the impact velocity has an effect on the incident and reflected signals. From equations (1) and (2), it is evident that the amplitude of the incident signal only depends on the impact speed and the bar material properties. When comparing the tests at a constant impact velocity and different temperatures (Fig 3.b), the incident signals are nearly identical (which confirms the good repeatability of the impact speed). The same is true for the reflected signals. These signals are not impacted by the temperature of the sample.

$$\sigma = \frac{1}{2}\rho C_0 V_{striker} \tag{1}$$

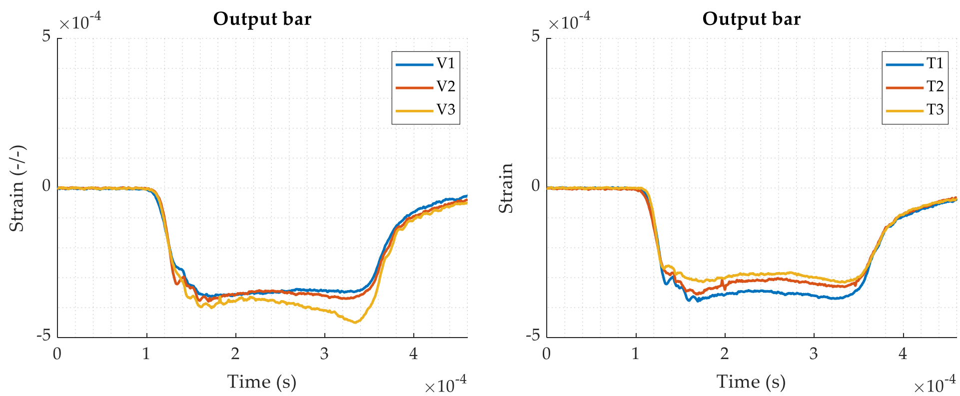
$$C_0 = \sqrt{E/\rho} \tag{2}$$



(a) **(b)**

Fig 3. Evolution of the strain in function of time, measured on the input bar: **(a)** at constant temperature (293 K) for 3 impact speeds (V1 = 6 m/s, V2 = 11 m/s and V3 = 13.2 m/s), **(b)** at constant impact speed (11 m/s) for 3 temperatures (T1 = 293 K, T2 = 373 K and T3 = 473 K).

For the signals measured on the output bar (Fig 4), there is a noticeable influence of the impact velocity and the temperature variation, when impacting the sample. An increase in velocity induces an increase in the amplitude of the signal, the opposite phenomenon occurs for an increase in temperature. However, the shape of the signals is preserved, except for the V3 curve of Fig 4.a.

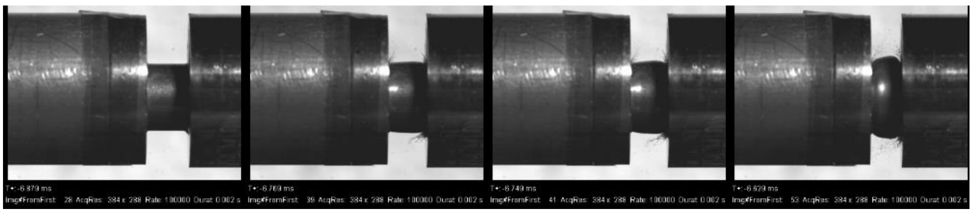


(a) **(b)**

Fig 4. Deformation curves measured in the output bar: **(a)** at constant temperature (293 K) for 3 impact speeds (V1 = 6 m/s, V2 = 11 m/s and V3 = 13.2 m/s), **(b)** at constant impact speed (11 m/s) for 3 temperatures (T1 = 293 K, T2 = 373 K and T3 = 473 K).

Therefore, the experimental study shows the samples dependencies on strain rate and temperature. This highlights the same dependencies for the same materials studied separately.

A series of images recorded at 11 m/s and 293 K is shown in Fig 5 . They show a non-uniform deformation of the sample with time. This is due to the particular geometry of the sample having a jacket bulge on the output bar side.



T = 0 ms T = 0.128 ms T = 0.148 ms T = 0.268 ms

Fig 5. Images of the SHPB test carried out on a core-jacket sample at 11 m/s, 373 K, captured at different times.

In the following part, the SHPB test on the core-jacket assembly is simulated in order to compare the numerical results with the experimental ones.

4 Comparison between experimental and numerical results

In this section, the numerical model of the previously presented tests is detailed. The finite element commercial software Abaqus® Explicit is used. The setup is fully modelled in a 3D environment. The striker, the input and output bars are meshed by linear hexaedric elements. Finally, a linear elastic model is assumed for their behaviour (respectively steel, steel and aluminium). The initial speed of the striker is given as the initial condition. The samples are composed of the two materials (lead and steel), each part meshed by linear hexaedric elements with a 0.32 mm size, a static friction coefficient of 0.6 [10] between the lead core and the tombac (CuZn) plated steel jacket is supposed. The cylindrical sample is presented on the Fig 1.b. The constitutive model of the lead alloy core is a custom perfect plasticity model taking into account the temperature and strain rate dependencies presented in [6] defined by equations, (3) and Table 1. The material was tested up to dynamic deformation ranges for different temperatures with an adapted SHPB setup.

$$\sigma_y = A.\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon_0}}\right)^n . \exp\left(-\frac{k}{T}\right) \tag{3}$$

Table 1. Perfect plasticity model parameters.

A [MPa]	n [-]	k [K]	$\dot{\varepsilon_0}$ [s^{-1}]
15.99	0.2285	-338.02	1850

The steel alloy jacket constitutive model is based on the Johnson-Cook plasticity model. The model takes into account the strain rate and temperature effects.
The contact between the sample and bars is assumed to be frictionless due to the lubrication during the experiment. The deformations measured by the gauges (numerical and experimental) are compared for the same test conditions and for the same position on the bars (Fig 6).
First, the signals on the input bar are studied. It is noted that the incident deformations are similar whether in time or in amplitude. This is consistent with the fact that they only depend on the initial conditions (striker velocity, materials and geometry of the striker and the input

bar) and are independent of the sample studied. It is therefore important to have this first good correlation of these deformations to be able to study the influence of the identified constitutive model for the materials of the ammunition. Concerning the reflected signals, the amplitude and shape are again similar whatever the velocity or temperature. For the transmitted signal on the output bar, it is noticeable that the shape of the strains is well reproduced in numerical simulation in terms of time duration and amplitude.

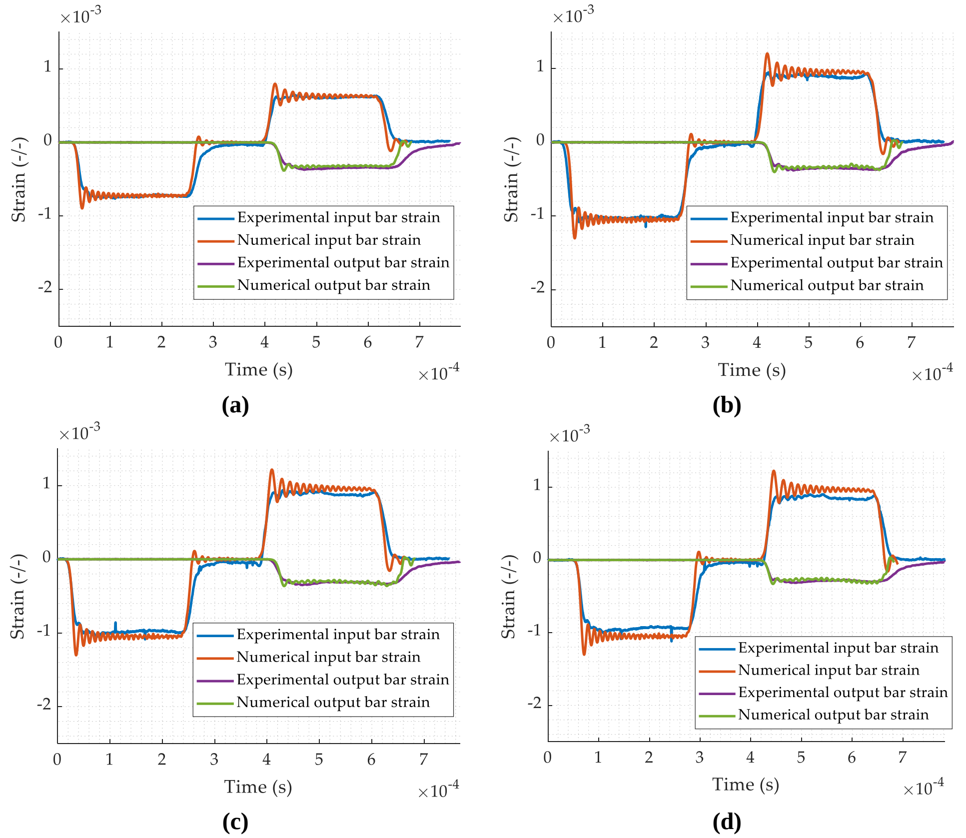


Fig 6. Comparison between the numerically and experimentally obtained strain for: **(a)** v_1 = 6 m/s at 293 K; **(b)** v_2 = 11 m/s at 293 K; **(c)** T_2 = 373 K at 11 m/s; **(d)** T_3 = 473 K at 11 m/s.

Numerical and experimental deformation faces of the lead core – steel jacket samples are compared in Fig 7. The latter images show that the simulated profiles reproduce the experimental sample shape relatively well. It is important to mention that the visual effect on the edge of the experimental sample is caused by the grease and cannot be seen on the numerical simulation. The non-symmetrical deformation due to the sample geometry is well numerically reproduced. The back of the ammunition gives more rigidity to this area and reduces the deformation as it can be seen at t = 148 μs and t = 268 μs, on the right of the sample.
This test has been computed numerically for different impact speeds and temperatures. It was able to match the experimental results with fidelity, not only for the signal measurement but also for the deformation faces.

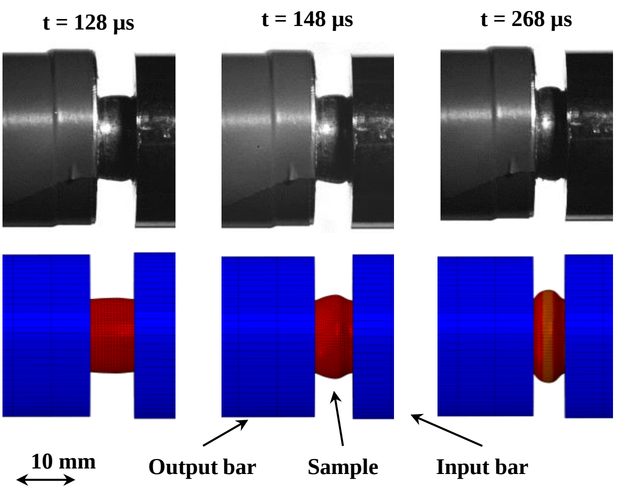


Fig 7. Comparison between experimental and numerical geometries observed during a SHPB test (striker velocity of 11 m/s, at room temperature).

5 Conclusion

The mechanical behaviour of the 9 mm ammunition, consisting of a lead alloy core and a steel alloy jacket, was investigated in this paper. For this purpose a preliminary study, not presented here, was carried out on both the lead core and the steel jacket separately. That data was then used to identify the parameters for constitutive models of each material.
SHPB test were performed on the lead core and steel jacket assembly, extracted from the ammunition, to validate the constitutive modelling of the ammunition as a whole. The experimental study concluded that the assembly was sensitive to strain rate and temperature. A numerical model of these tests was conducted in ABAQUS© Explicit. The comparison of the experimental and numerical strains of the input and output bar gauges pointed out a good correlation between the numerical and experimental results. The analysis of the sample deformation faces showed a similar representation of the behaviour.
The constitutive models identified for each material and the numerical modelling of the assembly were validated by those tests. The assembly numerical model can therefore be used for impact loading simulations. Nevertheless, for additional accuracy, it should be complemented by a failure model which is currently being investigated.

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