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Dynamic qualitative bolt force measurements for investigating influence factors on the pushout effect of small calibre ammunition

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ABSTRACT

A small calibre weapon system consists of the weapon and the ammunition. In the case of bolt action rifles during the process of firing, the breech is a rigid bearing which prevents the casing from being pushed out. However, not the whole pushout force is taken by the bolt. Due to friction forces at the casing boundary, the chamber of the weapon can absorb a significant part of the pushout force. The duration of the pushout force is in the order of milliseconds. Piezoelectric strain gauges are capable of recording such short time events qualitatively. To increase the measurability of force obtained from raw signal, is filtered using a bandpass filter and applying a signal envelope. The results from the strain gauges are verified by a piezoelectric force washer. In this paper, two different lubrication states and two different casing materials are analysed to evaluate their influences on the force absorbed by the bolt. The analysis indicated that lubricated casings lead to bolt forces which are more than three times higher when compared unlubricated casings. The unlubricated steel casing also showed a significant lower bolt force when compared with the regular brass casing. However, this effect is reversed, if the casing is lubricated. This work demonstrates how to measure highly dynamic events. The acquired results can be directly applied to 5.56x45 bolt action rifles. These measurements may also have a significant influence on self-loading rifles, since the process of reloading is also dependent on the pushout force. The general application area is target competitive shooting and military purposes.

INTRODUCTION

The process of firing a weapon system is a vivid example of the application of the Newton's third law. The gas generated by the burning propellant accelerates the projectile in the weapon until it leaves the muzzle. This acceleration process leads to recoil. During the acceleration, the casing of the cartridge experiences high pressure. This leads to high pushout forces, but for an extremely limited time. However, the chamber and the bolt of the weapon holds the cartridge in place during this time. See Figure 1.

The overall pushout force is not purely taken by the bolt of the weapon. The cartridge casing can be assumed as a pressure vessel which is plastically and elastically deformed during the time while the propellant burns in the chamber. Through this behaviour the casing is pushed against the walls of the chamber. Due to the friction between the chamber walls and the casing, the chamber of the barrel itself is capable of taking some of the overall pushout force.

The bolt force depends mainly on four factors: The surface area of the case head, where the pressure applies; the pressure in the casing; the friction between the chamber wall and the casebody; and the material properties of the chamber and the casing. The pressure curve in the chamber should be highly repeatable. Woodley et al. measured the projectile and the propellant mass which resulted in comparable pressure maximas.[1] Since the cartridges are produced in tight tolerances, the area of the casing head can also be assumed as constant. In these experiments, the pushout force is mostly dependant on the material properties of the casing and the chamber and the friction coefficient between these materials.

The behaviour of the dynamics of small arm weapons are often investigated using high speed cameras. However, these cameras are

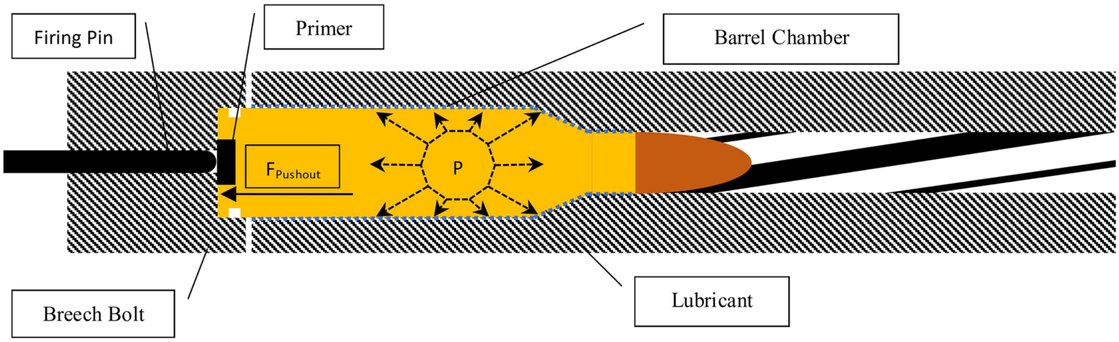

FIG. 1. Schematic view of the cross section of the barrel.

suitable only for visible events, so are not appropriate for bolt action rifle measurements. A breech bolt of a weapon holds the ammunition in place during firing. Often such short duration rigid or invisible processes have been modelled using finite element analysis.[2,3] The advantage of finite element methods is that numerous parameters can be investigated within in a single model by undertaking sensitivity studies. It is also possible to analyse geometric parameters with minor changes in the model. South et al. investigated an interesting interior ballistic model which can be used to estimate the behaviour of a projectile while being pushed through the barrel. Some aspects of the model correlated almost exactly with the reality, but the wear mechanism of the groove formation during the firing was not represented realistically.[4] It is still very difficult to simulate wear and tribological mechanisms such as friction and lubrication in thin film environments.[5]

It is also possible to measure these highly dynamic forces in a real environment. Ritter et al. presented a system to measure the in-chamber primer pushout force.[6] They used a force gauge to measure simultaneous the force on the breech and pressure inside the cartridge. This gave the confidence to predict what occurs in the chamber of the barrel. However, with this system it was only possible to measure the primer force which is produced during a fire. It is not possible to measure the whole force at the bottom of the cartridge.

Another possibility to measure highly dynamic events, such as vibrations, are piezoelectric strain gauges. Michaelides et al. used such strain gauges to analyse the movements of a vibrating bridge.[7] In their investigations they used the strain gauges for frequencies between 1 and 100 Hz. Such strain gauges are capable to quantify much faster events. The raw signal quality is good with such encapsulated strain gauges, so that it is possible to determine noisy but dynamical events with an adequate signal processing.[8]

Bin Tan et al. used standard flexible strain gauges to investigate the effect of steel balls, impacting at 200 m/s on military protection helmets. These strain gauges where used as a reference for validating the FE model.[9] Nevertheless, due to the rigid shape of the military helmets, piezoelectric strain gauges are not suitable for such an application.

One main problem of internal ballistics measurements systems is the noisy signals. The reason for this is that the acceleration process of a bullet is a short time event approximately 1 ms for the investigated calibre, which is comparable with a burst where a lot of mechanical oscillations are generated. In such a noisy environment one has to determine the main physical event of interest. A de-noising approach with discrete wavelet decomposition in combination with a Hilbert Huang transformation for the detection of faults in roller bearings was suggested by Phuong et al. They were more focused on reporting the time of occurrence of the fault.[10] To measure the amplitude of an event, wavelet decomposition is less suitable. For internal ballistic pressure measurements 20 kHz second order Butterworth lowpass filters are generally used.[11] In the case of pressure measurements it is simpler to determine the underlying physical event, such as oscillating pressure waves which may affect the whole measurement. However, in the case of the pushout measurement, more sophisticated filtering approaches are necessary.

Measuring force signals with piezoelectric force washers is widely used from the field of biomedical engineering[12] and the rock drilling technology.[13] Groche et al.[14] used a force washer to indirectly measure the applied force on a punch in a high speed press for a thick steel plate. The indirectly acquired signals where highly comparable to the signals of the measured directly. However, the system had to be calibrated for which they used a stroke rate of 300 strokes per minute. This meant that the duration of the event of interest was of the order of 100 ms.

More dynamical investigations conducted by Jun et al. and Zhang et al.[15,16] Jun et al. investigated the behaviour of spindle in a machining setup using an assembly of force washers. Due to the rotation speed of the spindle and the cutting tool, the cycle of the cutting process was between 50 and 5 ms, which is more comparable with the internal ballistic process which is in the range of 1μs to 1ms. Jun et al. conducted the in-depth investigation of the force washers properties under harsh circumstances. They obtained a very positive outcome for this dynamic application. Zhang et al. showed that even ultrasonic forces can be measured with piezoelectric force washers. Repetitive loads which are applied only for 40 μs applied can be accurately detected. Such timescales are comparable with ballistic tests.

MATERIAL AND METHODS

Two different casing materials were chosen to investigate the influence of the lubrication on the pushout force. In both cases the ammunition type M193 was used, it is a well-defined NATO

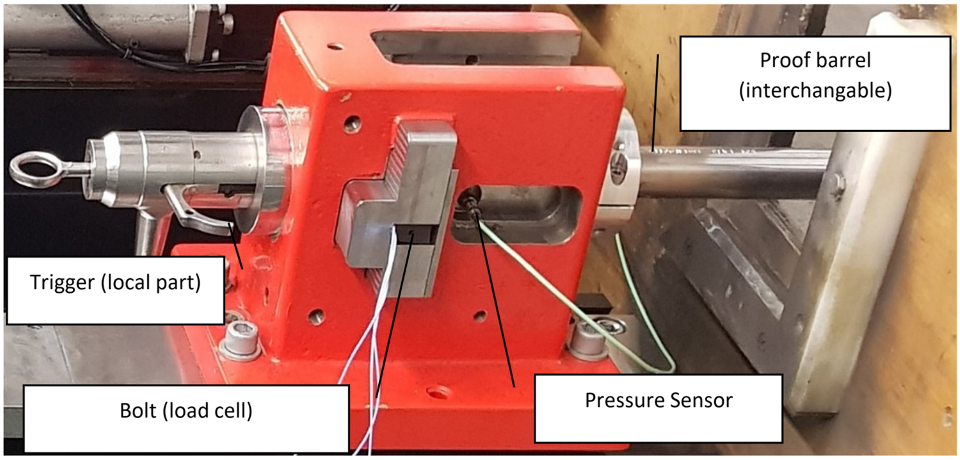

FIG. 2. Measurement System.

standard ammunition stock number.[17] This ammunition type has a projectile diameter of 5.56 mm and the length of the casing is 45 mm. The M193 has been extensively investigated by a number of researchers covering terminal ballistic studies.[18,19] Like some ammunition types, the M193 was produced with two types of casings, a regular brass casing and a steel casing.

To lubricate the casings a fluid called Klübersynt MZ 4-17 was used. This lubricant is recommended for small calibre weapons such as hunting and sporting rifles.[20] For the test, a thin layer of lubricant was applied onto the casing with a brush. The average weight of lubricant applied was 10 mg. The lubricant was equally distributed over the whole casing surface. The unlubricated ammunition was cleaned beforehand using acetone to remove any fat residuals, which might remain from the production process.

The ammunition was tested with a system similar to the Electronic Pressure Velocity and Action Time (EPVAT) measurement setup[21] which is known for NATO testings, see Figure 2. With this system, it was possible to measure the pushout force of the ammunition. Three piezoelectric strain gauges where pasted equidistance to around the load cell with an adhesive, see Figure 3a and 3b. The load cell consisted of stainless steel X5CrNi18-10, which is typically used in such experimental tests.[22,23] This material is also resistant to residue from the burned propellant which is highly oxidising in nature. In addition this load cell also acted as breech bolt, providing a rigid bearing for the ammunition, see Figure 3c.

Multiple sensors were used to analyse the effect of inhomogeneous loading during the acceleration phase of the bullet firing. To assist with vibration damping, the measurement system housing was manufactured from the cast iron. The gun barrels were similar to those used in an EPVAT system and were interchangeable and could be used for multiple calibres. The Kistler 6215 pressure gauge with a Butterworth 20 kHz filter was used as a reference system. The velocity was measured with a light gate. The pressure and velocity were measured in separate test setups.

The National Instruments USB-6366 data acquisition device was used for the tests. It has the ability to simultaneously acquire and record data every 0.5 µs. The piezoelectric strain gauges were of type 740b02 (PCB, USA). They are capable of measuring frequencies up to 100 kHz. In addition, a low pass filter to reduce the mechanical oscillations while measuring the pressure was used. The raw data with a signal amplification rate of 1, was acquired without filter using PCB-482C05 (PCB, USA) signal conditioner.

To verify the results of the piezoelectric strain gauges a precalibrated force washer was additionally used. This force washer gives a signal in volt, which can be directly converted into a force

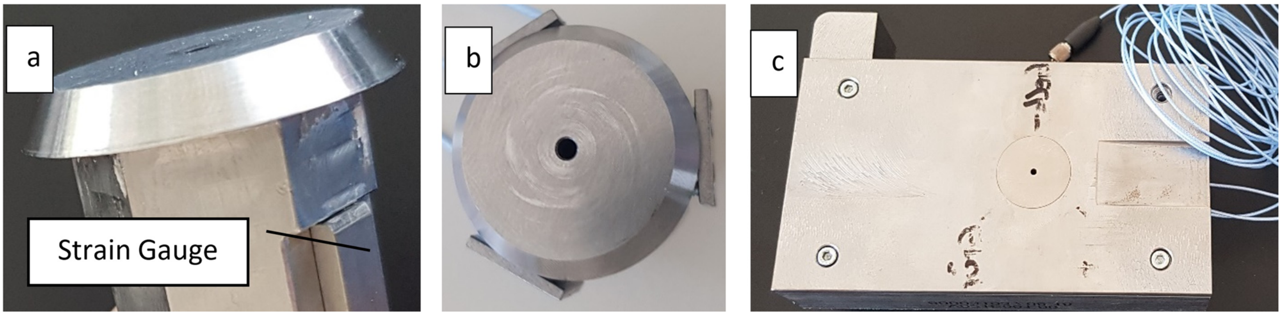

FIG. 3. Qualitative measurement assembly of the load cell (a) Load cell with strain gauge (b) Assembled load cell (c) Fully assembled breech measurement plate.

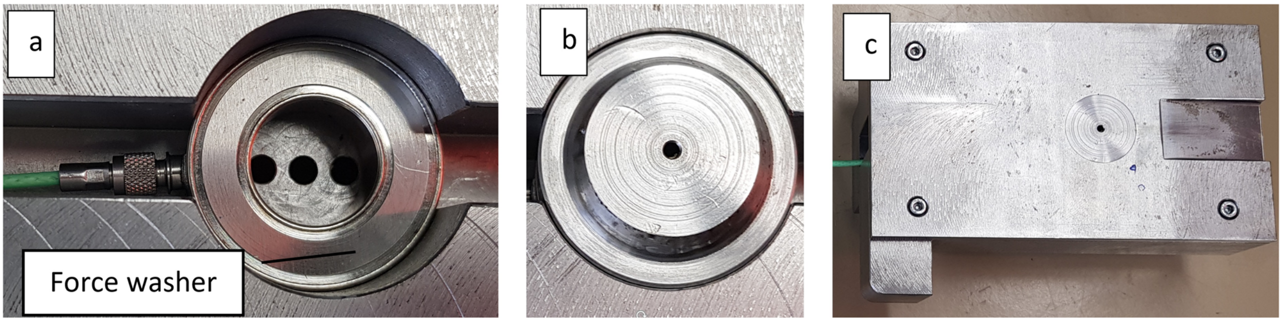

FIG. 4. Quantitative measurement assembly (a) Force washer (b) Protection Plate (c) Fully assembled quantitative breech measurement plate.

signal in Newtons. However, with this system it is not possible to detect asymmetrical loads produced by the casing.

The used force washer was a Kistler 9041a (Kistler, Switzerland), this sensor type is capable of recording forces up to 90 kN. The signal conditioner was a Kistler 5073A (Kistler, Switzerland). Figure 4 shows the assembly of the force washer. In Figure 4a one can see the sensor. However this sensor needed to be protected by a steel protection plate (Figure 4b). The second reason for the steel plate was to provide a rigid bearing for the ammunition. A large difference to the load cell which is equipped with piezoelectric strain gauges is that the measurement device and the rigid bearing is split into two parts.

The data acquisition time was set to 20 ms. As the signal of interest was ca. 4 ms, this acquisition time was sufficient. The pretrigger was set to 0.1 ms. The reason for this extended acquisition time was to ensure that the trigger started the data acquisition before releasing the spring loaded igniter rather than later when the igniter hit the primer. In this experimental set up, it was just possible to trigger the release time. Each test was repeated five times.

To investigate the signal linearity of the load cell with the piezoelectric strain gauges and the force washer, a servo press was used, which applied a defined load for a short time on the system. The servo press was controlled by a calibrated force detector and an additional sensor that controlled the servo press system. This double controlled system ensured the calibration accuracy.

After the shooting, the empty cartridge casings where optically investigated for any scratches or shape deformations. In addition, a longitudinal sectional cut of the empty casings was performed to investigate the case head area and the maximum internal diameter, see Figure 5.

The tests were performed in a closed shooting range behind safety glass. The cartridge was ignited by a remote trigger.

RAW DATA PROCESSING OF PIEZOELECTRIC STRAIN GAUGE SIGNAL

The Hilbert transformation which produces a signal envelope is a widely used function in signal processing, see Refs. 10, 24, and 25. It is especially used in the analysis of a signal that exhibits rapid increase and decay similar to internal ballistics.

A general property of the signal envelope is that a signal wave which carries a lot of high frequency noise can be demodulated into a low frequency signal which represents the main physical property, even if the signal is not cyclic. After transforming the signal into an envelope as shown in Figure 6, it can be used as a stand-alone signal. The signal envelop approach is most suitable for our application because it filters out high frequency peaks that are artefacts, deriving from reflections.

Tests showed that a reliable approach is to measure the force during firing with a combination of a bandpass filter and a signal

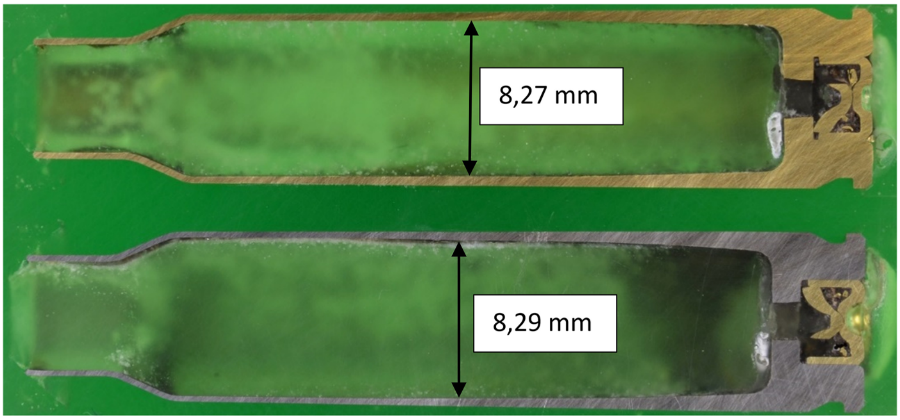

FIG. 5. Analysed casing types and their maximal internal diameter, the upper is the brass casing and the lower is the steel casing.

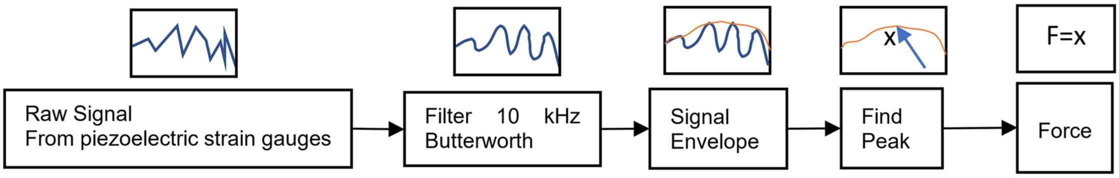

FIG. 6. Signal processing of the raw data.

envelope. Because of the signal characteristics, it is possible to work with the maximum value of the signal envelope to determine the maximum force.

As already mentioned, a servo-press was used to investigate the linearity of the system. However, such a press, only offers limited comparability with the real test situation. In the described system, the signal processing was undertaken exactly as in the real internal ballistic measurements. Therefore, the investigation was performed at its peak. This paper only investigates the linearity of the load cell, it is not aimed to calibrate the load cell to give fully quantitative results.

RESULTS

Figure 7 presents the raw data (in blue) of a typical force signal for all tested casing scenarios. The red dashed line represents the signal envelope: To compare the results, only the signal envelope was used. The duration of the signal is ca. 1 ms. One can note that the raw signal consisted of high frequency components, especially during the ignition phase. These parts are strongly reduced by processing the signal through a 20 kHz filter and generating the signal envelope. The signal envelope exhibits a strong smoothening. However, the time of the first excitation of the envelope is strongly consistent with the impact point of the raw signal. In the unlubricated brass case scenario, measured with strain gauges, the duration of the force is shorter compared to all other scenarios.

The force curves represented in Figure 8 show the post-processed raw signals of the lubricated and unlubricated brass casings measured with strain gauges. The amplitude is normalised relative to the regular case which is considered to be the unlubricated brass casing. One can observe that the starting time of the force generation on the breech is at the same time for both the lubricated and unlubricated casing. However, the peak force of the unlubricated casing falls at 0.4 ms, which is earlier when compared to the lubricated casing falling at 0.55 ms. This observation is for both measurement scenarios valid, for the measuring system with strain gauges and for the one with the force washer.

The unlubricated casing curves shows a lower peak force and in case of the strain gauge measurement a smaller deviation between the max and min peak force compared to the lubricated casings. The semi-quantitative difference is of the ratio of about 1:2 in both peak force and the deviation in the case of brass casings.

The difference between the lubrication scenarios can also be observed in Figure 9 and Figure 10. The variance in the case of steel casings is even stronger. The peak force both in the lubricated steel and the brass casing is exhibited at almost the same time.

However, the time when the force applies to the breech bolt is just marginally different for steel between the unlubricated and lubricated curves. This is contrary to both brass casing measurements, where the force from the cartridge applied on the breech for the unlubricated state acted for a markedly shorter time.

The comparison of some neuralgic data is represented in Table I. It shows a large difference in both the average and the maximum force between the baseline (unlubricated brass casing) and the lubricated casings, which is in both cases ca. factor 3. Even more

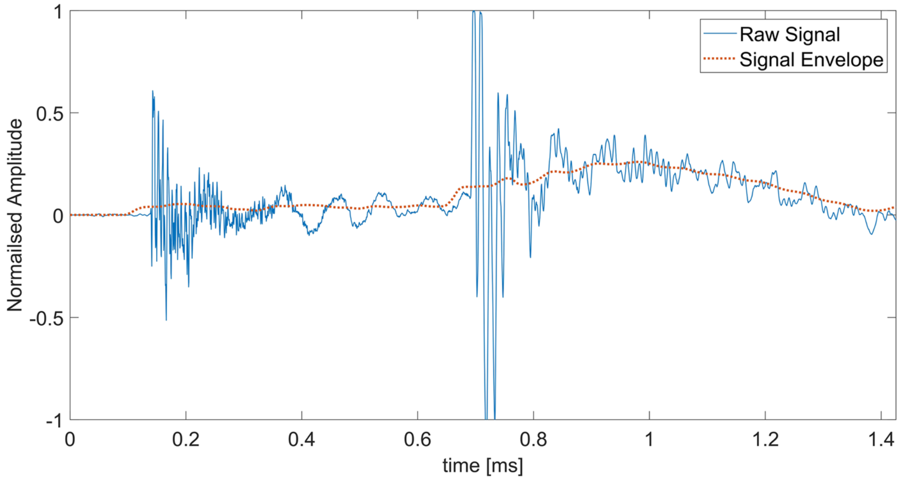

FIG. 7. The raw signal of the strain gauges and its calculated envelope.

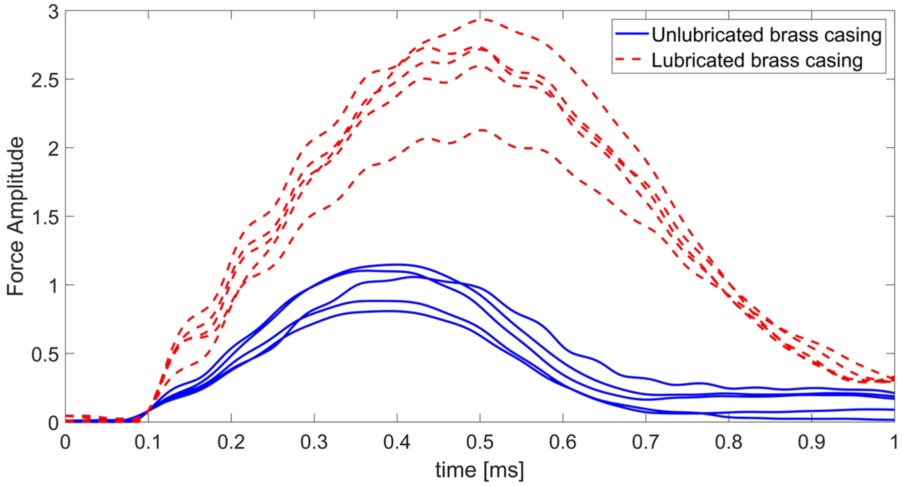

FIG. 8. The peak pushout force measured with piezoelectric strain gauges showing lubricated and unlubricated brass casings.

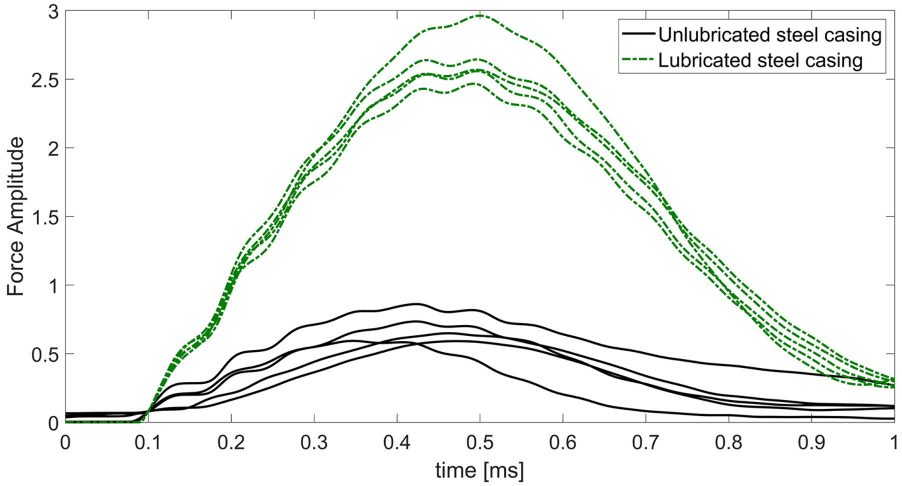

FIG. 9. Comparison of the force signals of lubricated and unlubricated steel casings, referring to the unlubricated brass casing.

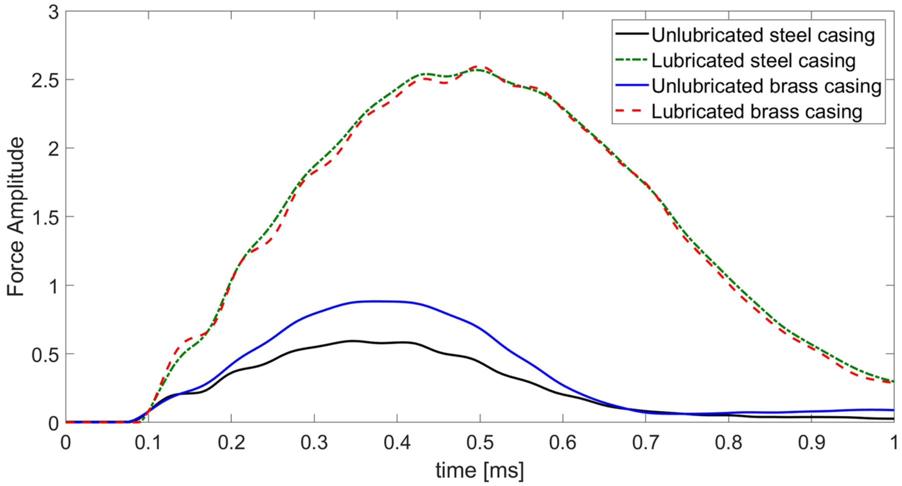

FIG. 10. Graph of average signals of steel and brass casings.

TABLE I. Relative comparison of the peek values of strain gauge measurements.

Description	Average Force	Min Force	Max Force	Average Pressure [Bar]
Brass Unlubricated	100%[a]	81%	114%	3510
Brass Lubricated	268%	212%	293%	3560
Steel Unlubricated	68%	59%	86%	3590
Steel Lubricated	264%	247%	296%	3509

[a] Normalised to the average of the unlubricated brass casing.

dramatic is the difference between the minimal and the maximum force of the steel casing which is approximately exhibiting a ratio of 1:5. In general, unlubricated steel casings produce less force on the breech compared to brass casings. The average reference pressure was acquired with a different measurement system. Each pressure test scenario was also repeated 5 times. The range of average pressures were highly comparable between the scenarios and overall, differences were negligible.

The results of the strain gauge equipped load cell were compared and verified by the force washer. To ensure consistency, the same apparatus such as the proof barrel, housing of the load cell and the trigger mechanism were used for all the experiments. Figure 11 shows the acquired data of the brass casings comparing the results from the force washer with the strain gauge measurements. The force washer signal was filtered with a 20 kHz filter. No signal envelope was applied during the experiments. In general, the results between the force washer measurements and the strain gauge based load cell are highly comparable. In the case of the force washer, a comparatively slightly faster decay to zero was observed in the lubricated brass casing. The comparative difference in the peak force decay is also noticeable in the lubricated casings. The relative average force, tabulated in Table II, indicates that the difference between the lubricated and unlubricated casing is around ca. 2.2 times. Similar magnitudes of relative peak measurements were captured by the strain gauges.

DISCUSSION

The results are consistent with the published models that used finite element analysis.[2] The measurements are conducted with two different approaches and are highly comparable which strengthens the outcome of key results. A change in lubrication leads to a significant difference in the pushout force. The signal processing approach described here is suitable for these force measurements. It was proven that the initial times of excitation remain the same while the main signal is strongly smoothened using signal envelop approach. This leads to a good comparability and comparison.

The engineered piezoelectric load cell as well as the force washer are suitable means of data acquisition devices to proof and measure the pushout force during the firing process. The main advantage of the force washer is that it is easy to get absolute values. If one wants to investigate the load distribution the measurement system with 3 strain gauges is more applicable.

The time during which the force is measured is comparable with the duration during which a projectile is pushed through the barrel. Despite the fact that forces are still expected in the chamber well after the projectile exits the barrel due to residual gas pressure in the chamber.

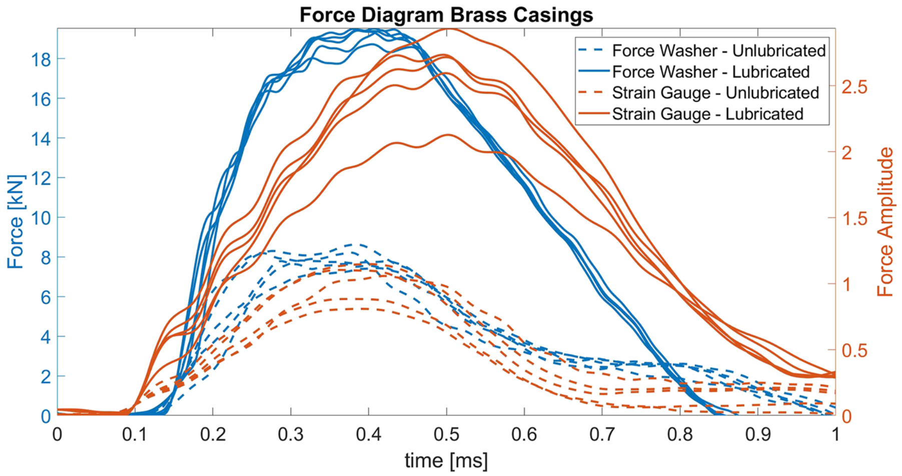

FIG. 11. Force washer signals during the process of firing in comparison to the signal from the strain gauge.

TABLE II. Peek force of the force washer measurements.

Description	Relative average Force	Average Force [kN]	Min Force [kN]	Max Force [kN]
Brass Unlubricated	100%	9.77	9.23	10.42
Brass Lubricated	217%	21.2	20.5	21.72

One significant observation from the analysis of these tests is that the lubrication in the chamber or on the ammunition leads to higher pushout forces. For reference, we have taken the unlubricated brass case as a baseline.

The mechanical material properties of the two casing types differ strongly. However, the fact that the lubricated brass casing produces the same pushout force as the lubricated steel casing leads to the conclusion that the pushout force is mainly depending on the friction between the boundary.

The comparison between the unlubricated steel and brass casing indicates that the steel casing produces significantly lower force on the breech. However, the duration of the load cycle in the case of the steel casing is comparatively longer, and in some cases, is more than 1 ms. The pushout energy remained comparable between the unlubricated steel casing and the unlubricated brass casing. It is important to note that the steel surface is treated with a lacquer. Due to this it is not possible to make statements about the steel casing-chamber interaction which has not been studied in this investigation, For a lacquered casing, the interaction is between the polymer and the steel chamber.

CONCLUSION AND FUTURE WORK

This paper demonstrates two approaches to measure the pushout force of the casing on the breech. The benefit of this system is that it can be used for calibres, such as 8.6x70 mm, which is frequently used by long range shootings with breech bolt rifles. An enhancement to this investigation are further tests with different small arm calibres, to investigate if casing geometries affect the push out force significantly.

These results might be also applicable for repeating rifles, since their mechanism is strongly dependant on the pushout energy, which strongly changes if casing is lubricated. It is also worth investigating the effect of water or ice in the chamber which may exhibit similar results. This technique would also be applicable for investigating the forces involved in breeches in larger gun systems such as autocannons and tank guns.

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