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Materiały Wysokoenergetyczne / High Energy Materials, **2023**, *15*: 71 − 80; DOI 10.22211/matwys/0240
ISSN 2083-0165

Research paper / Praca doświadczalna

Comparative tests of two types of nozzle closures for solid propellant rocket motors
Badania porównawcze dwóch rodzajów zatyczek dyszowych do silnika rakietowego na stały materiał pędny

Krzysztof Wacko*), Jan Kindracki, Przemysław Woźniak, Łukasz Mężyk

Warsaw University of Technology, Faculty of Power and Aeronautical Engineering, Institute of Heat Technology, 21/25 Nowowiejska Str., 00-665 Warszawa, Poland
* *E-mail:* krzysztof.wacko@pw.edu.pl

ORCID Information:
Wacko K.: 0000-0002-6128-6730
Kindracki J.: 0000-0002-3453-7776
Woźniak P.: 0000-0002-1952-0343
Mężyk Ł.: 0000-0002-2297-5672

Abstract: *The ignition of a propellant is one of the most important stages of a rocket motor operation, and so it is essential to provide the proper conditions for this to occur. The igniter used in such motors generates ignition gases, which increase the chamber pressure and temperature and initiate grain combustion. Hence, it is necessary to use a component which enables a sufficiently high pressure in the chamber for the combustion process to become fully developed and maintained. To this end, closures are used, which are pushed out of the nozzle once the required pressure is reached. In addition to ensuring proper ignition conditions for the propellant, they protect the grain from the adverse effects of e.g. weather (contamination, moisture). Proper selection of this component of motor reduces pressure accumulation time in the motor chamber, thereby improving the ignition characteristics, which in turn has a critical impact on the further combustion and performance of the motor. Experiments tested the adhesive bonding using 5 different adhesive types with the bonds being made at both room and increased temperature. For testing membrane, 3 materials were used: copper, brass and polypropylene, in which two thicknesses were tested: 100 and 200 μm. The results of the bonding showed high non-reproducibility and it was not possible to determine working pressure values with great confidence. However, for the membrane, the results were much more reproducible and a relationship was established between membrane diameter and its burst pressure, which may be put to practical use in tests or in micro rocket motor applications.*

Streszczenie: *Zapłon materiału pędnego stanowi jeden z ważniejszych etapów pracy silnika rakietowego, zatem niezbędne jest zapewnienie mu właściwych warunków ku temu. Stosowany w silnikach rakietowych na stały materiał pędny zapłonnik, generuje gazy zapłonowe, które podnoszą ciśnienie i temperaturę w komorze oraz inicjują spalanie ziarna. Dlatego konieczne jest zastosowanie elementu, który pozwoli na utrzymanie odpowiednio wysokiego ciśnienia w komorze, aby mógł się w pełni rozwinąć proces spalania. W tym celu stosowane są zatyczki, które po* *osiągnięciu odpowiedniego ciśnienia zostają wypchnięte z dyszy. Oprócz zapewnienia właściwych warunków zapłonu materiału pędnego, pełnią m.in. rolę ochrony ziarna przed negatywnym wpływem zewnętrznych warunków atmosferycznych (zanieczyszczenia, wilgoć). Odpowiednie dobranie tego elementu silnika pozwala na zmniejszenie czasu narastania ciśnienia w komorze silnika, poprawiając charakterystyki zapłonowe, co z kolei ma kluczowy wpływ na dalszy przebieg spalania i osiągi silnika rakietowego.*

Keywords: *solid rocket motor, nozzle closure, ignition, solid propellent*
Słowa kluczowe: *silnik rakietowy, zatyczka dyszowa, zapłon, stały materiał pędny*

1. Introduction

A rocket motor is a jet propulsion type which directly converts chemical energy into thermal energy by means of combustion and then into kinetic energy via the motor nozzle which propels the object [1]. The motor may operate in various environmental conditions: in the atmosphere, in vacuum or underwater, as it utilises only the resources stored on board [2]. One possible motor design is fuelled by solid propellant, whose characteristics include the ability to provide a wide range of thrust within a minimal period of ignition to full thrust. So, the initiating ignition of the motor is crucial to its proper operation. To improve the ignition process or even to enable it to occur in some cases, it is necessary to use a partition to separate the inside of the motor chamber from the external environment. This partition is most frequently referred to as the nozzle closure. The basic purpose of the closure is to help increase pressure in the motor chamber and to temporarily "hold" it, which results in an easier initiation of the reaction between the fuel and the oxidiser. Another purpose of the closure is to separate the inside of the motor from the external environment, which, as stated above, may be vacuum or liquid, which may impede or completely prevent ignition. Another important task is to prevent deterioration of the propellant and to maintain its proper structure and propelling properties, even with major time periods between its manufacture motor and its eventual use. The method of installing nozzle closures in motors fuelled with solid propellant may vary significantly and depends on the design, the technology available or the pressure conditions [3] at which the closure stops working thereby opening the outlet from the compartment for the exhaust gases, thus beginning the motor work phase noticeable from the outside. Closures may crack or be pushed out and the mechanical bonds between the closure and outlet nozzle may break [4, 5]. The authors compared two closure types: a bursting membrane and a closure being ejected after rupture of the adhesive bond. The experiments were based around a micro rocket motor used in gas-dynamic control systems, with the size of the tested nozzles and nozzle closures being adjusted accordingly. However, the obtained results may be extrapolated other rocket motor sizes, provided that the proper criteria are used: the critical diameter of the outlet nozzle and the operating pressure of the motor.

2. Test facility and test method

To investigate the operation of the nozzle closure, a special test facility was built, consisting of two main systems: hydraulic and data gathering. The test method adopted assumed that the generation of pressure to simulate the pressure accumulating in the motor chamber was continuous, until the burst or ejection of the closure. Figure 1 shows the components utilised in the testing. The hydraulic system consisted of a manual hydraulic pressure pump (2) with duct, cross piece (1) to connect the outlet nozzle under test (5), the design of which varied slightly depending on the test closure type, and the filling system with venting (3). The hydraulic medium for test purposes, by which the actual operating pressure of the motor was modelled, was demineralised water, which ensured an appropriate safety level for the personnel. The measurement system consisted of a pressure sensor (4) by Keller PAA-23 with the measurement range adjusted to the experimental conditions (typically the measurement range was 2-200 or 0-400 bar, a measurement card by National Instruments USB 6259 with a sampling frequency of 50 kHz and a computer with in-house acquisition software.

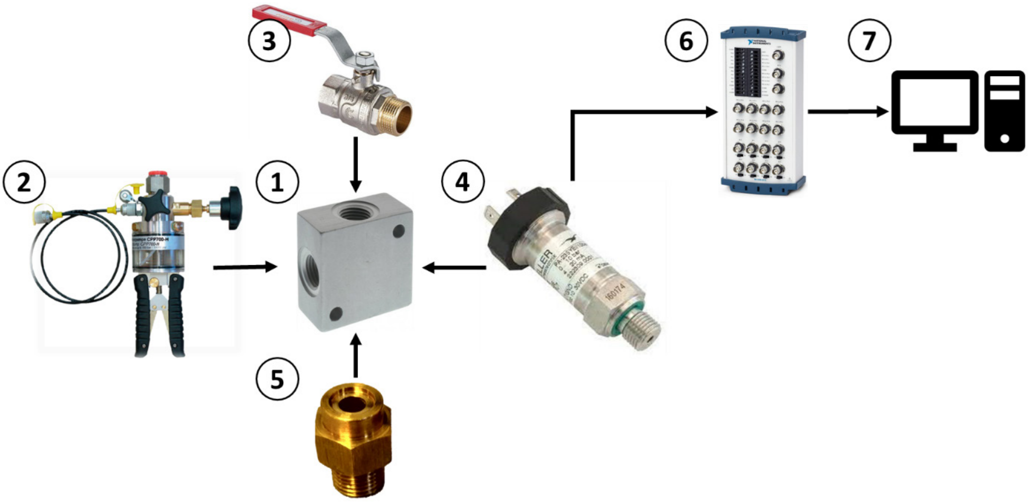


Figure 1. Measurement system diagram: 1 – cross piece, 2 – hydraulic pump CPP700-H [6], 3 – ball valve [7], 4 – pressure sensor Keller PAA-23SY [8], 5 – sample mounting component, 6 – measurement card NI USB6259 [9], 7 – computer

The test consisted of placing a nozzle with a pre-determined critical diameter closure in a hydraulic system, priming the system with the chosen hydraulic fluid and venting it, then initiating the measurement and increasing the pressure within the nozzle until rupture of the membrane or ejection of the closure. At that moment, the test was ended, measurement stopped and the highest pressure recorded in the system noted. That pressure was taken as the limiting value. At this point, it should also be noted that the actual pressure change processes within the motor chamber are much more dynamic, so the obtained values are somewhat higher than in the actual dynamic rocket motor start-up process.

3. Preparation of adhesive-based nozzle closures

Experiments validating the suitability of an adhesive were performed on two closure shape concepts (with flat and conical adhesive bonded surface) and several different materials: steel, brass and plastic (trade name Ertalon or PA 6). The different tested closure variants based on adhesive bonding, between the closure surface and nozzle, is shown in Figure 2. For the experiments, several sets of two-component epoxy adhesives were tested. A list of the adhesives used, with their basic parameters, is shown in Table 1.

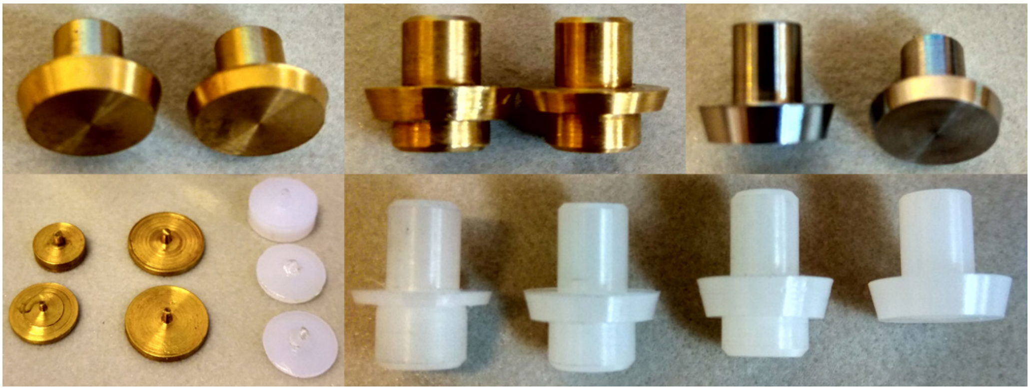


Figure 2. Nozzle closure concepts tested using adhesive bonding

Table 1. Properties (parameters) of tested two-component epoxy adhesives

Adhesive (trade) name	**MultiBond-1201**	**Monolith SE 105-1**	**Monolith EP 2501-1**	**Loctite EA 3422**	**Loctite EA 3421**
Tensile strength [N/mm^2]	28	–	–	28.6	28
Shear strength [N/mm^2] (brass)	28	5	25	3-5	2.5-4.5
Hardness (Shore D)	–	–	–	70-80	70-80
Limit life [min]	3-5	90	3-4	3-4	180
(Initial) full curing time [h] (room temp.)	24	(24) 48	(<1) 72	2	36

The tested closures and sample mount components were thoroughly prepared. Before every adhesive application, the closure surface was thoroughly cleaned and degreased, with the adhesive being prepared as recommended by the manufacturer. The prepared samples were then cured in open air (approx. 20 °C) or in a heated dryer (approx. 40 °C) until such time as full curing of the adhesive was achieved. The experiment, the procedure of which was described earlier, was performed at room temperature or with the bonded closure with the mounting component cooled to a temperature of –25 °C, while the samples were cooled in a chiller. Closure testing at low temperatures is connected with the possibility that the motor may be required to operate at low temperatures. Thus, it follows that the bond between the closure and the nozzle should retain its properties at low temperatures.

4. Preparation of nozzle closures in membrane form

For testing nozzle closure membrane, three materials were selected which were considered suitable for use in small size rocket motors. Copper and brass sheet with a thickness of: 100 and 200 µm as well as polypropylene film with a thickness of 100 µm, was proposed. A set of test membrane mounting components of different internal diameters in the range of 2 to 12 mm (Figure 3), was prepared.

Figure 3. Set of test membrane mounting components for testing diameter series: 2, 2.5, 3, 4, 5, 6, 8, 10 and 12 mm

Membrane thicknesses and diameters for a given material were selected based on the authors' experience, and were expected to yield under the pressure of interest i.e. 100-300 bar. For membrane, testing was only carried out at room temperature.

5. Experiment results

As reported above, testing of both types of nozzle closures was performed in the same test station using the same pressure sensors, so that the results could be compared reliably. Adhesive closure tests were performed on 5 different two-component epoxy adhesives at different closure geometries and two different materials. The adhesive bond was prepared at room temperature or at elevated temperature, in a laboratory dryer. In total, 60 different test cases were obtained and more than a thousand experiments conducted, which resulted in an extensive measurement database. Figures 4 and 5 show a typical measurement series for two adhesives at two different adhesive bond cure temperatures: 20 °C and 40 °C. To increase the repeatability of test samples, 14 samples were prepared every time the epoxy adhesive was applied on suitable surfaces and then cured under identical temperature conditions. As shown in these plots, despite the utmost care, the rupture pressures of the adhesive bonds, differed significantly. The average pressure values for Loctite 3421 at curing temperatures of 20 °C and 40 °C were: 130 and 200 bar, with the differences between the minimum and maximum values being: 60 and 90 bar, respectively. The difference between the average adhesive bond burst pressure values is also significant and shows that despite the recommendations of the adhesive manufacturer, complete bond conditioning influences the time required to obtain the maximum strength (the temperature increase shortens that time). The bond conditioned at higher temperature shows a higher burst pressure. A partial explanation of this may result from the reduced air moisture absorption in drying conditions at higher temperature, in the closed loop drier. Both cases are characterised by low repeatability of the burst pressure, confirmed by the determination of the coefficient R^2 for the examples shown. This adhesive bond behaviour may be influenced by several factors, some of which may be identified as varied surface porosity, which contributes to the surface wetted by adhesive or the not fully reproducible manual adhesive application process, despite following manufacturer recommended procedures. Other test cases were similar in this respect.

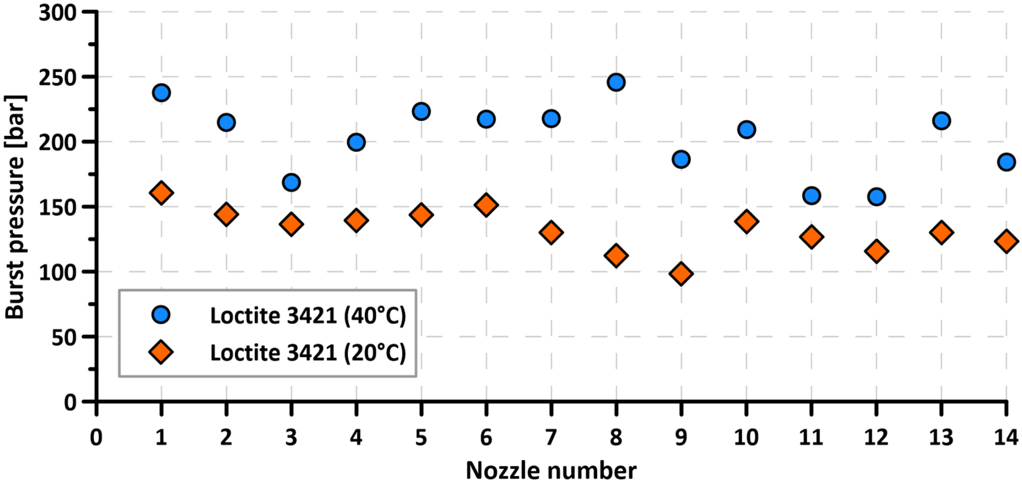


Figure 4. Example burst pressure values for Loctite 3421 and two test cases – different bond preparation temperatures, closure material – MO58 brass alloy

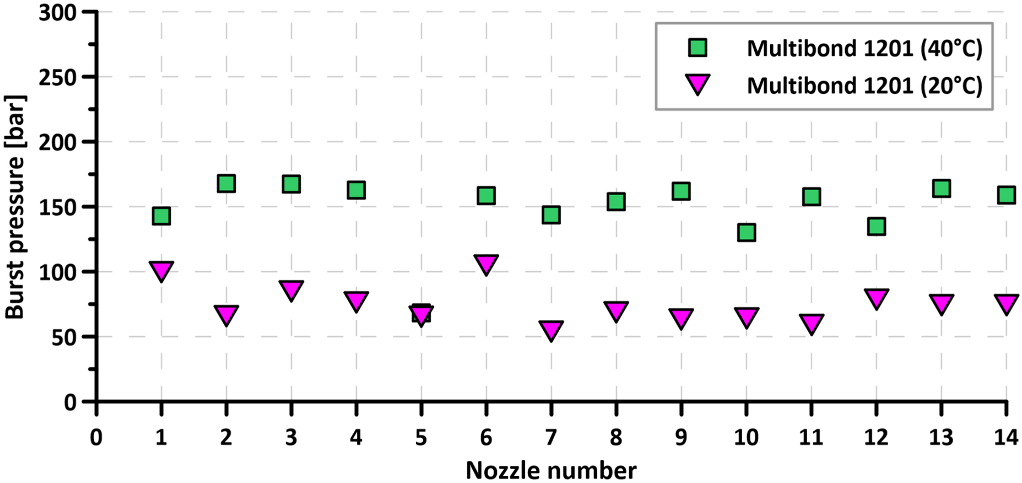


Figure 5. Example burst pressure values for Loctite 3421 and two test cases – different bond preparation temperatures, closure material – MO58 brass alloy

Another type of tested closure was in membrane form. Due to the nature of their operation, the burst pressure is proportional to the membrane diameter (surface area of exhaust gas pressure). As mentioned above, 5 different cases were tested: two copper and two brass films and one polypropylene membrane. Figure 6 shows the membrane burst pressure as a function of its diameter. The nature of the experimental point distribution confirms the assumption that the higher the average value, the lower the pressure required for burst to occur.

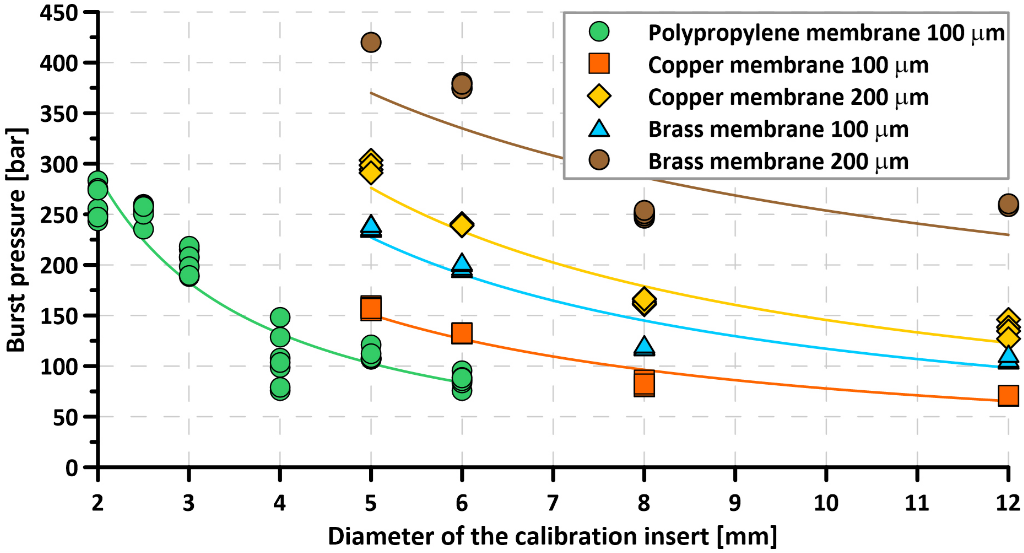
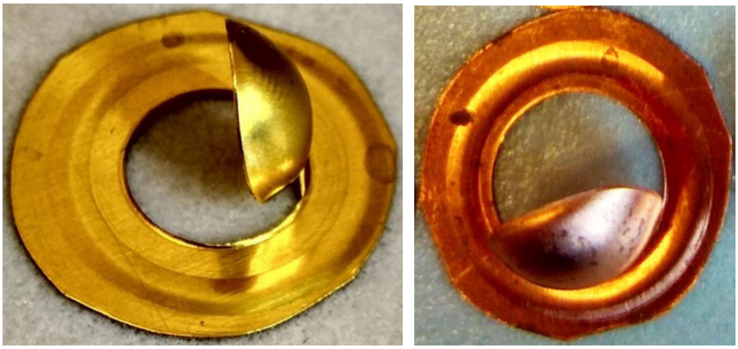


Figure 6. Burst pressure values related to the calibration insert diameter for tested membrane materials

Table 2, in turn, shows the coefficients of the power function describing the relationship between membrane diameter and its burst pressure, and the correlation coefficient R^2. All results, apart from the brass membrane with a thickness of 200 µm, show a correlation of above 85%. Of course, the use of membrane is associated with a more complicated bonding mechanism, i.e. the necessity of sealing and proper mechanical pressure between the two surfaces. Its destruction consists first in plastic deformation followed by crack propagation along the holding edge (Figure 7), which is reminiscent of the situation of punch-cut components. Membrane burst may look different in pre-cut cases, distributed e.g. radially. However, with such a small membrane thickness and its application in the nozzle outlet cross-section, pre-cutting for de-fragmentation is not necessary.



(a) (b)

Figure 7. View of the membrane (200 µm sheet) after the experiment: brass (a) and copper (b)

Table 2. Summary of parameters of equations of the power function adjusted to experimental points for the tested membrane materials

Functional relationship form: p[bar] = A * (d[mm]) ^ B			
Material	**Coefficient A**	**Coefficient B**	**Adjustment coefficient R^2**
Polypropylene film 100	630	–1.127	0.873
Copper sheet 100	703	–0.956	0.916
Copper sheet 200	1222	–0.924	0.911
Brass sheet 100	1057	–0.955	0.889
Brass sheet 200	888	–0.544	0.564

The membrane bursting and solid rocket propellant sample combustion initiation process is presented in Figure 8. The membrane was mounted in the laboratory micro motor, in the nozzle outlet diameter and pressed in place with a sealing ring. In the sequence of 6 photos shown, it can be noticed that the increasing pressure in the chamber causes plastic deformation of the membrane. Once the pressure limit is exceeded, it ruptures along the edge between the diverging part of the outlet nozzle and its retaining pressure ring. In this case, the membrane of brass of appropriate thickness served its purpose and enabled the accumulation of pressure in the combustion chamber up to the required value, which contributed to the proper development of the propellant's combustion process.

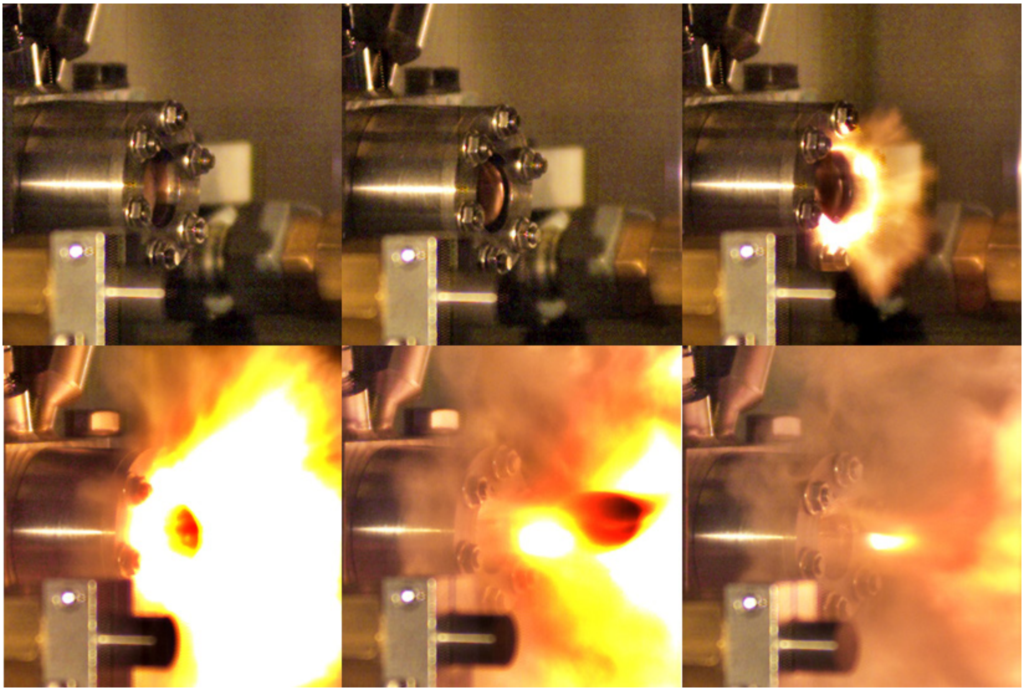


Figure 8. Membrane operation sequence during propellent sample combustion in laboratory micro rocket motor

6. Summary and conclusions

- This study compared two nozzle closure types: in the form of a bursting membrane and the closure being pushed out after adhesive bond rupture. The experiments were performed on a purposely prepared rig with a hydraulic pump acting as a generator of simulated pressure in the combustion chamber. In the testing of the bonded closures, several different closure shapes were tested: flat and conical bonded surfaces, manufactured from: stainless steel 1.4301, brass MO58 and plastic (Ertalon). Bond strength was tested using 5 different, readily available, two-component epoxy adhesives. The closures were bonded to components corresponding in shape to the nozzle of the micro rocket motor. The prepared samples were cured in open air (approx. 20 °C) or in a close dryer (approx. 40 °C) for the time required to ensure full curing of the adhesive bond.
- The experiment consisted of exerting pressure, which causes rupture of the adhesive bond, thus determining the maximum pressure under which this phenomenon was observed. In total, 60 different cases were tested: different adhesives, as well as closure shapes and materials. Based on more than 1000 experiments, it was concluded that despite the utmost care taken in preparing the adhesive bond, the subsequent obtained bond burst pressures, varied significantly. It was noticed that the conditioning of the bond (curing at 40 °C) contributed to the higher burst pressures obtained. A possible explanation for this could be an increased ambient moisture absorption in the sample curing conditions, at higher temperature. It should be emphasised that in both curing regimes, the time to reach maximum strength of the adhesive bond was selected according to the curing temperature recommended by the adhesive's manufacturer.
- Another factor influencing the significant non-reproducibility of the results could be due to slight differences in the roughness of the bonded surfaces, as well as the not entirely reproducible manual adhesive application process, despite the utmost care being taken.
- Another tested type of closure was in membrane form. 5 different variants were tested: two copper films with a thickness of 100 and 200 µm, two brass films with a thickness of 100 and 200 µm and polypropylene film with a thickness of 100 µm. The recorded rupture (membrane burst) pressures were proportional to the surface area of the membrane (Figure 6). This relationship was determined using the power function, in which the equation coefficients and coefficient R^2 for each tested material was presented in Table 2. The results obtained show a correlation at a level of above 85%, except for tests involving brass sheet 200 µm. The specific nature of pressure changes related to the surface area is the same, regardless of the thickness of the membrane of the given material. Thus, the results could be extrapolated to greater membrane diameters, after selective verification of several test points.
- Although the experiments on adhesive bonds did not provide positive results, the authors do not exclude this closure mounting method. The tests described were only performed on closures for small motors, in which the impact of the roughness or the non-uniformity of the manual application of the adhesive layer was disproportionate, however for larger surface areas, this would diminish. This fact may be confirmed with further research work.

Acknowledgements

The results obtained form part of a study in the project "Development of the executive system components design for gas-dynamic rudders", 2017-2018 (industrial project), and internal works of the Aircraft Engine Division of the Faculty of Power and Aeronautical Engineering at the Warsaw University of Technology in 2017-2019.

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Received: August 31, 2023
Revised: December 19, 2023
First published on line: December 21, 2023