Development of Exploding Foil Initiators for Future IM

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ABSTRACT

For Missiles, expensive Insensitive Munitions and other timing dependent munitions applications (e.g. aimable or tandem warheads) the so-called Exploding Foil Initiator (EFI) is widely used as the detonator in the initiation train. These devices are still inefficient, relatively big and rather expensive. The development of a Micro chip (Mc) EFI is therefore desirable but needs an efficiency improvement of the system before it can be miniaturized.

An Exploding Foil Initiator consists of a small capacitor charged to a high voltage, a switch, a transmission line, an exploding foil and an explosive. When the capacitor is discharged via the transmission line into the metal foil, the foil will explode and propel the flyer to a velocity of more than 3 km/s, high enough to initiate the explosive on impact. For the development of an Exploding Foil Initiator (EFI) the following topics are of interest: the electrical circuit, the exploding foil, the velocity of the flyer, the driver explosive, the secondary flyer and the acceptor explosive. In this initiator, the driver explosive accelerates the secondary flyer that initiates the booster explosive.

In the recent years, TNO has conducted research on this topic, mentioned above, to improve the efficiency of an EFI, resulted in a mini-EFI, and is a development platform for a Micro Chip EFI in the near future. Besides measurement techniques to measure the efficiency, research has been carried out to arrive at an optimal flyer form (length, width and thickness) and material, length and width of the barrel, density of the driver and acceptor explosive in a secondary flyer set-up. This has led to a system that works at 1300 V (current of 3 kA) and delivers 90% of the electric power to the foil. Because of this high efficiency, instead of a spark gap, a solid state switch is used in the mini-EFI design. It also leaves the door open for further miniaturisation to the McEFI in the near future, possibly resulting in a low cost EFI that can be used in gun launched munitions.

Several test series have been performed with a variation of the acceptor explosives, in a secondary flyer set-up, like TATB and RDX/wax at several densities and a variation of the secondary flyer material. Also progress has been made in the development of more powerful driver explosives like insensitive nano crystal nitramines (RS-RDX, RS-HMX and Cl20). The results of the development process and the test series will be presented.

Keywords: EFI, flyer velocity, explosive, initiation, detonation, IM

1. INTRODUCTION

In most munitions, standard initiators with primary explosives are used, often being a source of trouble for IM compliance, and also leading to many unwanted unexploded devices in the battle field. So-called Exploding Foil Initiators (EFIs) have big advantages over standard initiators, because they are intrinsically safer (because instead of primary explosives secondary explosive are used), more reliable and work much faster. They are also more compliant with the new STANAG (4560) regulations and give new opportunities for munitions development. At this moment, Exploding Foil Initiators (EFI) are used only in expensive and timing dependent munitions systems. These devices are still inefficient and relatively big and also very expensive. The development of a Micro chip (Mc) EFI is therefore desirable but needs an efficiency improvement of the system before it can be miniaturized. TNO has started the investigation to improve this efficiency to open the door for future miniaturisation.

Figure 1 shows the schematic drawing of an Exploding Foil Initiator (EFI) that consists of a small capacitor charged to a high voltage, a switch, a transmission line, an exploding foil and an explosive. When the capacitor is discharged via the transmission line into the metal foil, the foil will explode and propel the flyer to a velocity of more than 3 km/s, high enough to initiate an (secondary) explosive. The driver explosive accelerates the secondary flyer that initiates the booster explosive.

For the understanding of the functioning of an EFI and the development of a reliable EFI the following topics are important: the electrical circuit, the exploding foil, the velocity of the flyer, the driver explosive, the secondary flyer and the acceptor explosive. Several of these aspects have been investigated to optimise the efficiency of an EFI system. The less energy is used in the system the smaller the components become, giving the opportunity of down-scaling the system and the use of a solid state switch (instead of a spark gap). This is the first step necessary to open the door for the development of a Micro Chip EFI (McEFI).

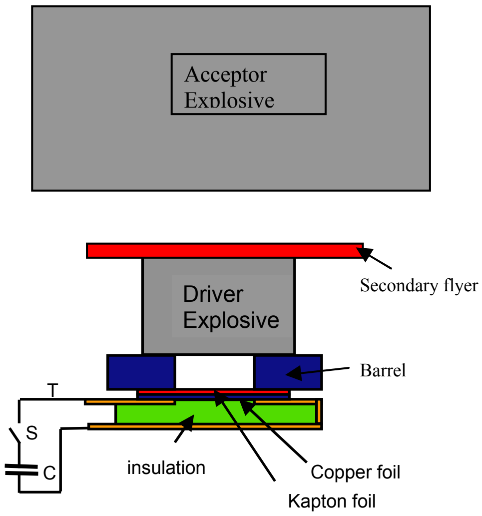

Figure 1. *The different features of an EFI and the subsequent detonation train are illustrated. The closure of the switch discharges the capacitor in the copper foil. It will explode and propel the kapton flyer. At impact the driver explosive will detonate and subsequently propel the secondary flyer that will initiate the acceptor explosive.*

2. DEVELOPMENT OF MEASUREMENT TECHNIQUES

2.1 Introduction

Making it possible to optimise the efficiency of an EFI and thus the design of the EFI, several aspects of the EFI, such as dimensions of the foil, foil and tamper material etc. have to be investigated. In order to investigate the influence of these parameters, one should be able to measure parameters such as the velocity of the flyer, the current going through and voltage over the system in order to obtain the energy deposited in the flyer. Several measurement techniques have been developed for this purpose and because of the high currents and voltages, leading to extreme electromagnetic fields, some of them are optical techniques. In the next paragraphs a short overview of applied techniques is given.

2.2 Velocity measurement

For the measurement of the flyer velocity, a Fabry-Perot Velocity Interferometer System (F-PVIS) has been used. In figure 2, a schematic overview of the Fabry-Perot system is given. Laser light, 514 nm Argon Ion laser of 1 W, is directed to the flying object by means of a multimode fibre. The fibre is terminated with a GRIN-lens to collimate the light on the object, and also to collect the reflected light into the fibre. The interferometer consists of an etalon of Burleigh Instruments type RC 150 with coated mirrors. The first mirror has a slit in the coating in order to increase the light efficiency in the etalon. The streak camera records the interference pattern. The velocity of tiny objects < 0.1 mm can be recorded with a resolution 50 m/s. The time resolution is limited by the etalon settings and the camera resolution but for most experiments around 2 ns. For more details on the design of the Fabry-Perot system see ref 1 and ref 2.

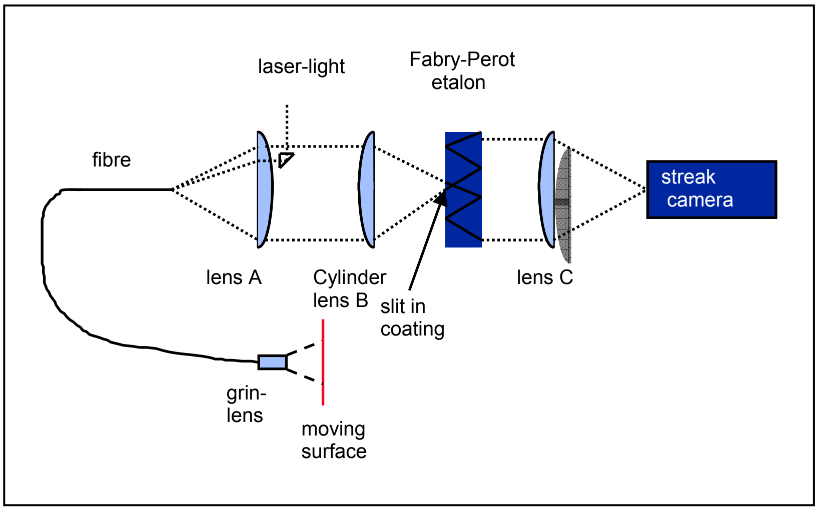

Figure 2. *The main parts of a Fabry-Perot Interferometer system. Laser light (514 nm) is directed to the moving object with a multimode optical fibre. The reflected light is transported to the Fabry-Perot etalon with the same fibre. The interference pattern is recorded with a streak camera*

With this equipment the influence of the dimensions of the exploding foil and the flyer on the velocity and the acceleration of the flyer are investigated. Also the integrity of the flyer during flight has been analyzed. An example of the acceleration of the flyer in an EFI is given in figure 3.

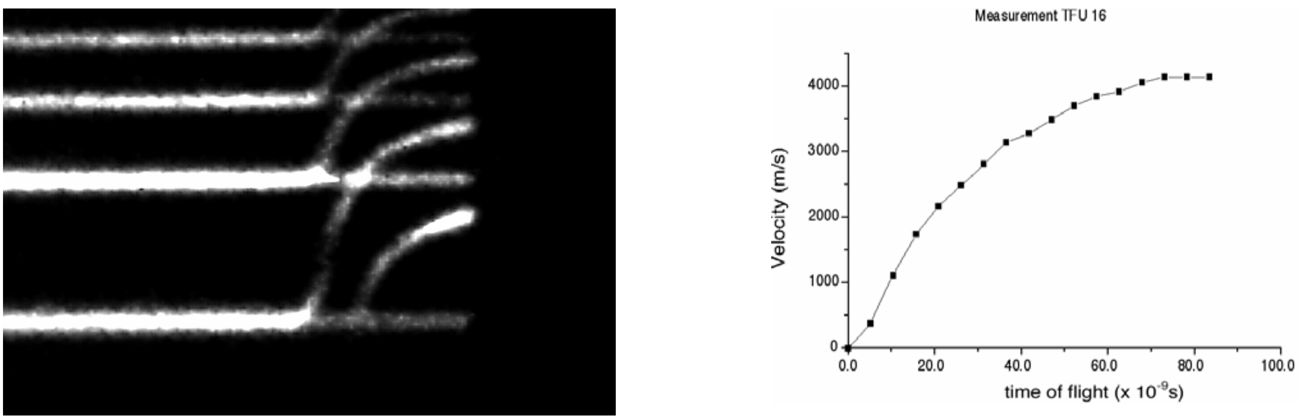

Figure 3. *The left picture (3a) shows the interference pattern of the Fabry-Perot of this flyer. The right side (3b) is the velocity as function of time of the flyer.*

The velocity of the flyer can be calculated from the interference pattern with the aid of the next equation:

$$v = F_c \cdot \left(i + \frac{D_j^2(v) - D_j}{D_{j+1}^2 - D_j^2} \right)$$

With *v* the velocity of the object, *Fc* the fringe constant. This fringe constant depends on the wavelength and the mirror spacing. *D* the diameter of fringe, *j* the order of interference and *i* the integer depending *v*.

Specifications: 2 < *Fc* < 10 km/s, rise time: 2 ns, resolution: 50 m/s

The F-PVIS also reveals other important information. One may .e.g. detect the unwanted situation that the flyer breaks up in pieces during acceleration as the light of the flyer is lost. This may happen when the acceleration is too high, but also when the barrel is too long. The velocity is obtained by integration of the velocity profile also the velocity as function of the distance. Experiments with variation in the thickness of the tamper material have revealed that, in case of a short circuit, the malfunction can not be detected by the examining of the electrical signals but only by the acceleration profile of the flyer.

2.3 The fibre optic probe (FOP) for detonation velocity measurements

At TNO a sensor has been developed that monitors the build-up of a detonation but is *insensitive* to electromagnetic fields. This optical sensor, called the fibre optic probe or FOP, is more suitable for use in this environment than other techniques that are based on electric signals, like ionisation pins and resistance wire. Because of its small diameter (0.5-1 mm) it can also be used in small samples of explosives without interference.

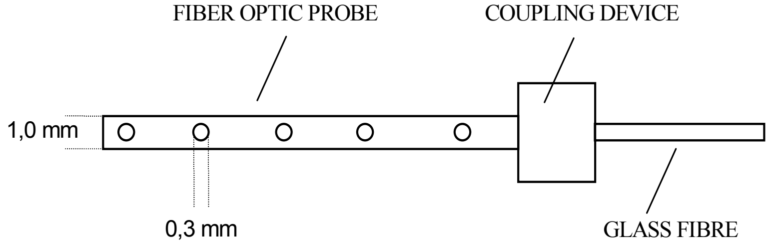

Figure 4. The Fibre Optic Probe (FOP).

The FOP is a fibre with several holes in it, see figure 4. The passage of a shock or detonation wave compresses and ionises the air confined in a hole, which gives a pulse of light. The light pulse is transmitted through the FOP, a glass fibre, and an optical attenuator. An optical-electrical converter allows recording with a digital signal analyser. In the experimental work presented here the maximum number of holes in a fibre has been limited to twelve. The diameter of the FOP and the holes are 1.0 mm and 0.2 mm, respectively. Stray light produced by the detonation that can intrude in the fibre is minimised by means of a silver-paint coating. The positions of the holes are measured with a microscope. With the recorded signal of the detonation process, showing sequential light pulses (see example in figure 5), it is possible to determine the time of shock wave passage for each hole. Together with the distance of the individual holes, the velocity of the shock wave can be calculated. An example of such a profile is given in figure 6, which is calculated from the measurement given in figure 5 (HNS II, 97% TMD, initiated by the impact of a 125 µm flyer). Figure 6 shows the build-up of the detonation wave, the value of the stable detonation velocity and the initiation distance of the explosive. The error in the final detonation velocity is typically about 200 m/s.

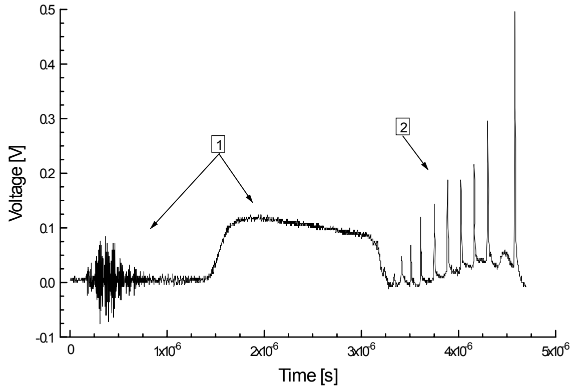

Figure 5. An example of a recording of the FOP, with number 1 pointing out the interference of the trigger pulse of the MAP and the light produced by the FPA during the flight of the flyer, number 2 points out the signal produced by the compression of the holes in the FOP.

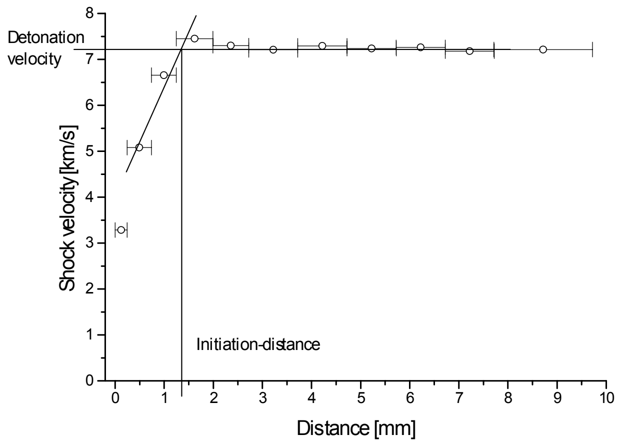

Figure 6. The corresponding (to figure 5) shock wave velocity and the initiation distance.

3. EFFICIENCY IMPROVEMENT

3.1 Importance of flyer velocity

The flyer velocity is the most important parameter that determines whether the initiation of the explosive is successful or not. The initiation is governed by the following equation:

$$E_{crit} = P^2.\tau$$

This is the so called Wasley criterion that means that every explosive needs a certain minimum energy before explosion occurs. Herein is P the impact pressure in the explosive when the flyer hits the target. This impact pressure depends on the velocity of the impactor and shock impedance of the explosive and the impactor. The length of the pressure pulse, τ, depends on the thickness of the impactor. Besides the velocity and the thickness of the impactor, the diameter has to be larger than a certain critical value an which varies for different explosive materials.

3.2 Exploding Foil and electric circuit optimisation

The only purpose of the optimisation of the electrical circuit is to accelerate the flyer as efficiently as possible, to reach the highest velocity with a minimum of energy stored in the capacitor. Therefore the electrical discharge circuit consisting of the capacitor (low loss capacitor), the switch and transmission line and the exploding foil has to be optimised in order to reach maximum efficiency. The influence of the dimensions of the foil on the flyer velocity has been investigated. Parameters as length, width, thickness, shape and materials have been varied to obtain a maximum flyer velocity. Also the shock wave impedance of the tamper (see figure 8) is of importance to obtain maximum velocity. Several series of experiments have been performed to optimise the electronic circuit. Due to these improvements and therefore a lowering of the working voltage to 1300 Volt, a solid state switch could be embedded in the design which is an improvement on itself. All these optimizing steps have led to an increase of energy deposition into the foil from just 50% to about 90%.

The exploding foil is confined between two sheets of Kapton. Figure 7 shows a top view photograph of a generic EFI and figure 8 a cross-section. The exploding foil itself consists of a narrowing in the copper transmission line. The current will mainly heat this part of the foil. When a critical current and current rise time is exceeded, the foil will turn into a plasma. The plasma pressure and the Lorentz forces of the current will accelerate the flyer through the barrel. Besides the dimensions of the exploding foil, the confinement of the foil is of great importance.

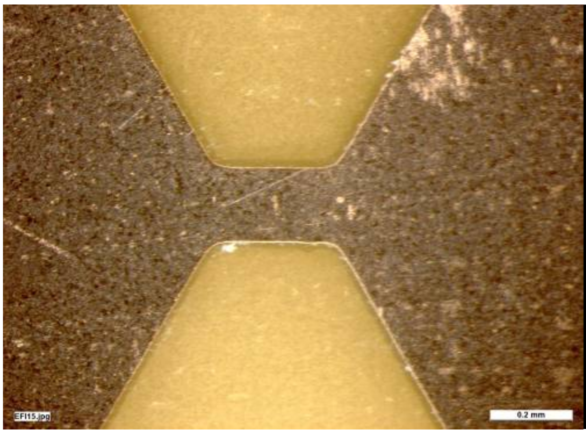

Figure 7 Top view of the exploding foil of an EFI, it consists of a narrowing in the copper transmission line.

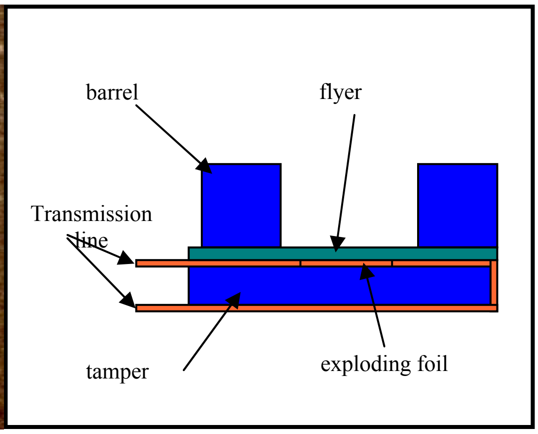

Figure 8 Cross section of the exploding foil initiator. The exploding foil will turn into plasma and is confined between the tamper and the flyer. The flyer is accelerated through the barrel

During the capacitor discharge the tamper (see figure 8) material acts as an electrical isolator for the high voltage that will exist across the transmission line during discharge. The thickness and shock impedance of the tamper are also important for the reflection of the shock wave in the direction of the flyer. It should be as hard as possible to prevent indentation by the shock wave and prevent a short circuit between the upper and lower part of the transmission line. A last minor aspect is the length of the barrel (figure 8). It should be long enough to reach maximum velocity, see e.g. figure 3b. The graph shows that at the end of the curve a maximum velocity of about 4000 m/s is reached.

3.3 Initiation behaviour of recrystallised HNS

The explosive material mostly used in EFI's is HNS IV. At TNO HNS IV has been recrystallised from HNS II, to get a grain size that is sufficiently small to be initiated by the flyer impact of an EFI. An example of recrystallised HNS IV is given in figure 9. The average grain size is around 400 nm, and can be further improved by decreasing the length to width ratio. To characterize the explosive material, to be used as driver explosive in EFI's, the initiation behaviour of the explosive has been investigated by taking pictures of the explosion with a high speed framing and streak camera (Hadland 468 camera). The experimental set up can be seen in figure 10.

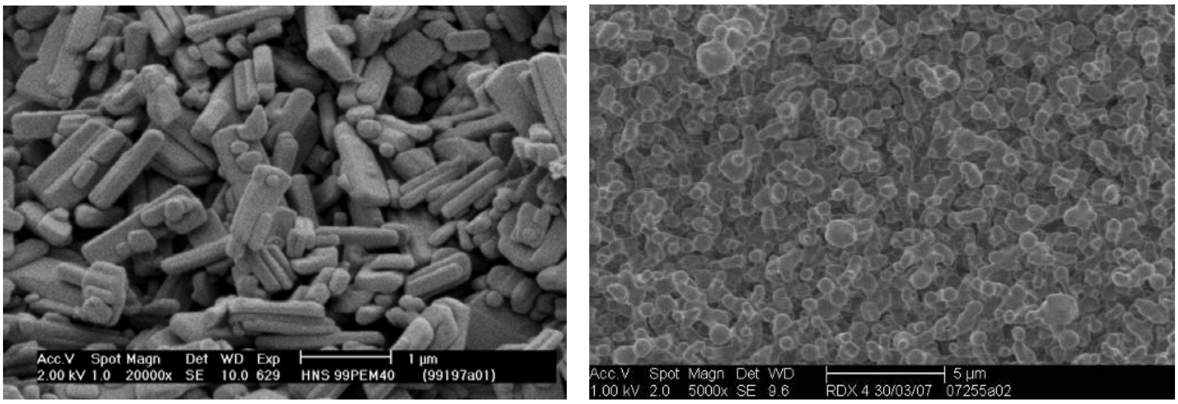

Figure 9. *SEM photograph of HNS IV recrystallised from HNS II for application in EFI's and on the right side sub-micro/nano RDX.*

The explosive pellet is glued on the transmission line against a PVC-block. The central axis of the cylindrical pellet coincides with the streak of the framing-streak camera. The explosive pellet is free standing pellet, pressed to a density of 90 %. No confinement is used, making it possible to observe the expansion of the detonating explosive.

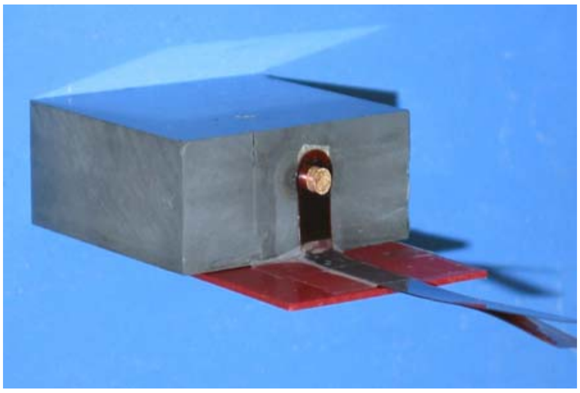

Figure 10. *Experimental set up for the initiation of the driver explosive by an EFI. The HNS IV pellet is glued on the transmission line.*

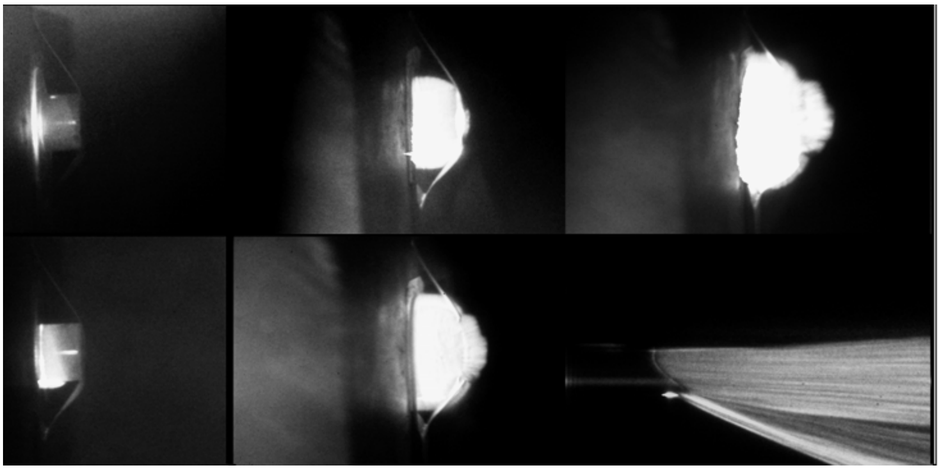

Figure 11. *Framing pictures of the initiation of an HNS-pellet by an EFI, and a streak picture that shows the initiation distance and the built up to detonation.*

The pictures are taken with exposure times of 200 ns at intervals from 200 ns. As the detonation velocity of HNS at this density is around 7 mm/µs, a total streak time of 1µs is sufficient to record the initiation and detonation behaviour of the pellet. From the streak record the initiation distance can be measured and also the build up to detonation. The slope at the end of the pellet determines the final detonation velocity of the pellet (figure 12).

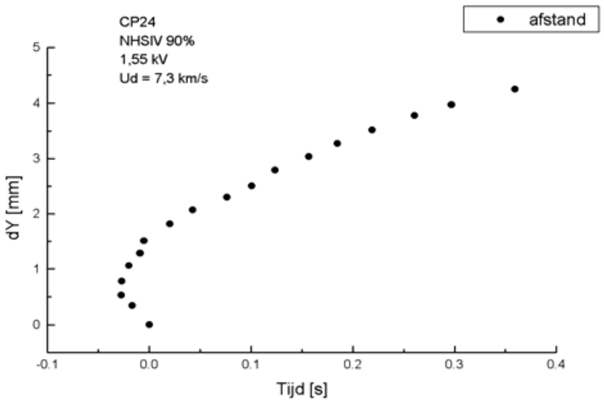

Figure 12. Initiation distance and detonation velocity of a HNS IV pellet initiated with an EFI.

To understand the initiation process even better, simulations have been carried out with the hydro code Autodyn. In the simulation there is no PVC block present and gases can expand in all directions. A comparison of the photograph of figure 11 and the simulation in figure 13 shows that the results are in good agreement.

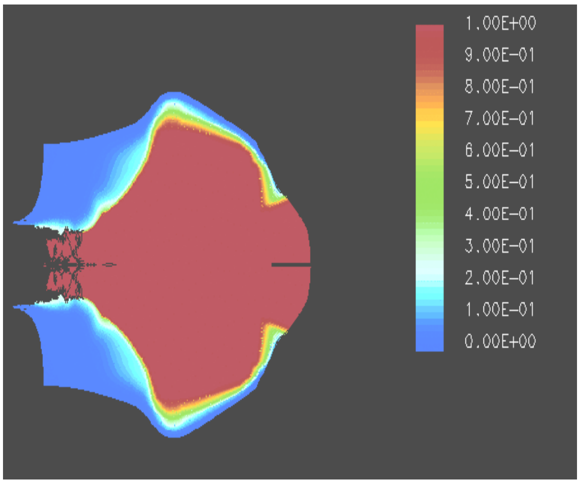

Figure 13. The result of an Autodyn simulation of a flyer impact on HNS IV.

HNS is known to have a relative low output. To have more initiation power in the future, RDX could be an option. Progress has been made in the recrystallisation *nano*-RDX. In figure 9 (right-hand side), a sample of sub-micron/nano RDX is shown.

3.4 Initiation of the booster explosive (secondary flyer)

In most detonation trains, the driver explosive of the initiator is in direct contact with the booster explosive. This booster explosive is embedded in the main charge. The possibility to initiate a (booster) explosive by means of a secondary flyer has been investigated. Figure 1 shows a schematical representation of the set-up. The secondary flyer can be made of variety of materials, like aluminium, stainless steel (SS) and polyester with different thicknesses. It is thought that the initiation of the secondary explosive, by means of such a flyer, could be more effective than by a direct contact. The reason for that is that the explosive needs only a short and powerful shock pulse to be initiated according to the critical energy criterion. To verify this hypothesis the acceleration of the secondary flyer is measured with the F-PVIS. This reveals the influence of the thickness and density of the flyer on the acceleration and final velocity. Several flyer materials and flyer thicknesses have been tested. One example of a stainless steel flyer is depicted in figure 14. The final velocity is around 1400 m/s. With this flyer, TATB, a very insensitive explosive could be initiated. In the next table these results have been summarized.

Table 1. *Explosive-flyer combinations tested in the secondary flyer impact configuration*

Flyer material	TATB (ρ = 1.688 g / cm3)	TATB (ρ = 1.842 g / cm3)	Hexocire (RDX/wax)
0.15 mm Stainless Steel	+	-	+
0.25 mm Stainless Steel	+	-	+
0.35 mm Mylar	+	-	+
0.3-0.5 mm Aluminium	+	-	+
0.43-0.55 mm Kapton	-	Not tested	+
0.81 mm Kapton	-	Not tested	-

The results of the experiments with different flyers show that initiation of TATB depends strongly on the density of the explosive. Mylar seems to be more effective in initiation than Kapton although both flyers have about the same density.

During the velocity measurements of 0.15 mm stainless steel flyers, two velocities have been observed with the F-PVIS as shown in figure 15. This time the Optronis SC-51 streak camera equipped with an MCP and a high resolution 16 bit CCD camera (1392 x 1024 pixels) has been used. These two pathways are probably caused by spalling as a result of the pressure wave from the explosive followed by a strong tension wave in the flyer. An overview of the mechanisms that play a role in the reflection of shock waves in composite materials can be found in ref 1.

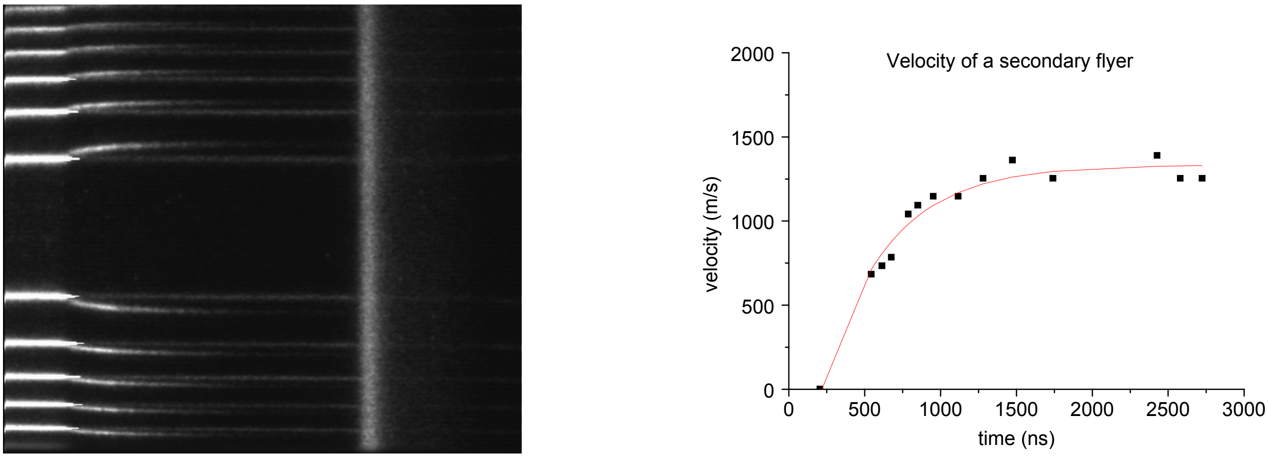

Figure 14. *Fabry-Perot interferogramme of the velocity of the secondary flyer and the velocity as function of time diagram of a 0.25 mm stainless steel flyer.*

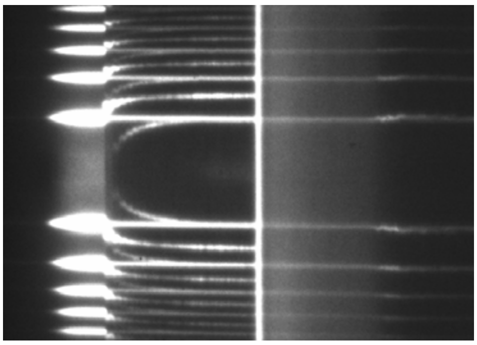

Figure 15. *Acceleration of 0.15 mm stainless steel flyer by an HNS IV pellet. Two velocities are visible and the impact of the flyer on the GRIN lens.*

4. DEVELOPMENT OF A MINI-EFI – ROAD TO MC-EFI

The next step of the investigation is the design, development and construction of a so-called mini EFI that also can be used as a developer platform for a Micro chip EFI (McEFI)). Several transmission lines with the exploding bridge and Kapton foils are designed and manufactured, HNS IV is recrystallised and pressed to the desired densities. Several electronic components have been carefully chosen and ordered. All electronic components are commercial Off-the-Self components of the electronic industry. Figure 16 shows a photograph of this mini-EFI

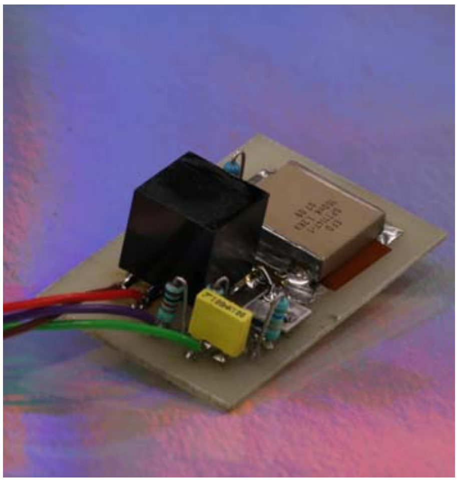

Figure 16. A prototype of the current mini-EFI, also used as a development platform for the Mc-EFI

5. CONCLUSION

For about two decades TNO puts effort in the investigation of shock characterisation of explosives by means of an EFI system. Recent years the research has focussed on the increased efficiency of the EFI system to lower the energy needed to accelerate the flyer to such a velocity that it is capable to initiate secondary explosives with a minimum of energy. The lower the energy needed the smaller the components become. The final goal is an *inexpensive* Micro chip EFI system that can be used in many applications not only in the defence industry but also in products on the civil market.

In order to determine the increases in systems' efficiency, several measurement systems have been developed to measure flyer velocities, the build–up of the detonation wave in the (booster) explosive and the power /energy deposited in the flyer.

In the next step, the transmission line, exploding bridge and capacitors have been improved and already optimized such that a solid state switch could be embedded in the circuit. This optimized system is capable to initiate an HNS IV pallet at a voltage lower than 1300 Volts. Other aspects as the length of the barrel, the tamper material, the flyer material etc have been investigated. Tests have been performed to investigate secondary flyer impact on explosives like TATB and RDX/wax with various flyer materials.

A validation of the system has been carried out by means of a high speed camera recording of the explosion of HNS IV after a flyer impact. These recordings have been compared with Autodyn computer simulations and are in good agreement.

Finally, a new design of a prototype mini EFI has been made and the prototype has been assembled and will be tested thoroughly in the coming months. A next step will be the design of a cost effective micro chip EFI for e.g. gun launched munitions or applications on the civil market.

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