Development and Testing of Hermetic, Laser-Ignited Pyrotechnic and Explosive Components

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ABSTRACT

During the last decade there has been increasing interest in the use of lasers in place of electrical systems to ignite various pyrotechnic and explosive materials. The principal driving force for this work has been the requirement for safer energetic components which would be insensitive to electrostatic and electromagnetic radiation. In the last few years this research has accelerated since the basic concepts have been proven viable. At the present time it is appropriate to shift the research emphasis in laser initiation from the scientific arena or whether it can be done to the engineering realm or how it can be put into actual practice in the field.

Laser initiation research and development at EG&G Mound has been in three principal areas: 1) laser/energetic material interactions, 2) development of novel processing techniques for fabricating hermetic (helium leak rate of less than 1×10^{-8} cm^3/s) laser components, and 3) evaluation and testing of laser-ignited components. Research in these three areas has resulted in the development of high quality, hermetic, laser initiated components. Examples are presented which demonstrate the practicality of fabricating hermetic, laser initiated explosive or pyrotechnic components that can be used in the next generation of ignitors, actuators, and detonators.

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INTRODUCTION

Present-day explosive and pyrotechnic devices, which include detonators, ignitors, and actuators, are functioned by applying an electrical signal to one or several bridgewires [1,2]. This is accomplished by sending the signal through the metal pin(s) (which are electrically isolated from each other and the metal shell by an insulating material, usually a ceramic, glass, or glass-ceramic) to the bridgewire. The energy transferred via the bridgewire is used to ignite the energetic material. In order for the component to function successfully, the selected insulating material must form a high-quality seal with the pin(s) and with the shell [3-4]. In many applications, the seal must be leaktight or hermetic (helium leak rate of $<1 \times 10^{-8}$ cm^3/s) and of sufficient strength to ensure successful functioning of the component.

Over the years bridgewire devices have been employed in systems despite having several inherent safety limitations. These safety concerns are based on the fact that the explosive or pyrotechnic material is not truly isolated from its surroundings, making these components susceptible to the effect of outside electromagnetic radiation. This safety consideration has been the driving force for the design of a new family of laser-ignited components that would be impervious to spurious levels of electromagnetic radiation. It is envisioned that laser components, which are insensitive to various high-risk environments, will eventually replace classical bridgewire components in many applications.

Past research on the laser initiation of energetic materials has centered primarily on understanding or measuring the interaction between lasers and these materials [5-8]. This work successfully demonstrated that laser ignition of energetic materials is feasible and, most importantly, reliable. Over the past few years research in this discipline has shifted from a scientific emphasis to one of engineering centered on the development of actual hermetic, laser-ignited components [9-14]. These components can be functioned by a variety of lasers, including laser diodes, which produce a sufficient output energy through an optical fiber to ignite the energetic material. These safer laser components require the fabrication of high-strength, hermetic seals with small-diameter optical fibers or transparent windows. The emphasis of this paper is to demonstrate the feasibility of fabricating hermetic, laser-ignited, explosive or pyrotechnic devices that could be used in the next generation of ignitors, actuators, and detonators.

Three principal design configurations (Figure 1) are under development for fabricating laser initiated components: 1) Direct Fiber Placement, 2) Fiber Pin, and 3) Transparent Windows. Each of these approaches has certain identifiable strengths and weaknesses depending on the required application. This paper will present examples of each type of component and some illustrations of firing results which have been obtained.

Direct Fiber Placement Components

As shown in Figure 1, Direct Fiber Placement components contain a length of optical fiber hermetically sealed within the component. In these devices, one end of the optical fiber is located at the former "bridgewire surface," while the other end "pigtails" out of the device for several centimeters or meters which then could be used for connecting to a laser or to another connector. The principal advantages of this type of design are: 1) the number of connections between the component and the laser is reduced, which minimizes losses due to interfacial reflections, 2) the optical fiber is sealed within the device, thus eliminating alignment problems, and 3) close tolerances can be obtained since the fiber is in final position prior to sealing.

The principal difficulty in the fabrication of Direct Fiber Placement components has been in developing processing techniques which result in a hermetic glass seal between the optical fiber and

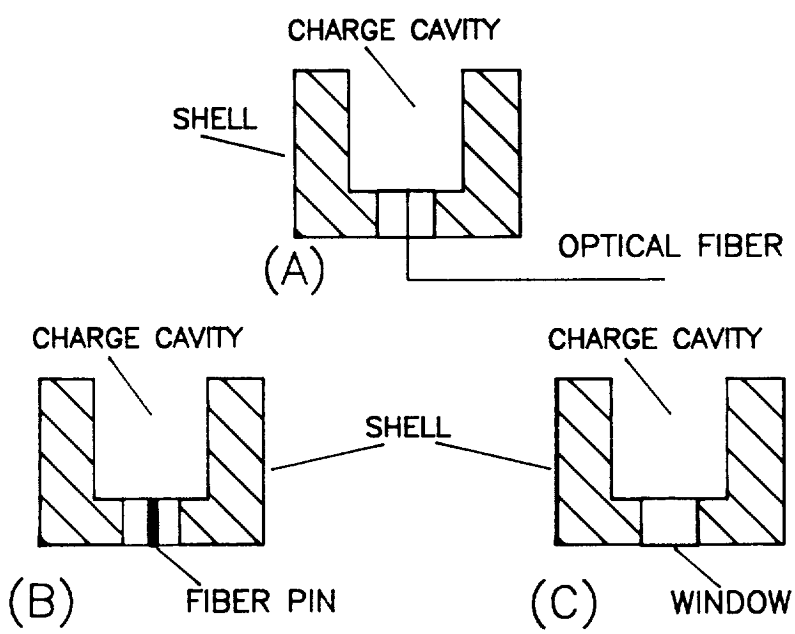

Figure 1 - Comparison of the three principal design configurations under consideration for laser-ignited components: (A) Direct Fiber Placement, (B) Fiber Pin, and (C) Transparent Window.

the sealing glass and between the sealing glass and the structural member or shell. This is difficult to accomplish without cracking the optical fiber due to the large coefficient of thermal expansion mismatch (alpha) between typical fused silica optical fibers (alpha ~8 x 10^{-7} cm/cm/^{0}C, 25 to 400^{0}C) and the shell material such as a stainless steel (alpha ~170 x 10^{-7} cm/cm/^{0}C, 25 to 400^{0}C). However, the Direct Fiber Placement component shown in Figure 2 was successfully fabricated using one of several Fiber Insertion Processing techniques which have been developed [15]. These components were fabricated using a SMA 906 alumina ferrule connector (obtained from Optical Fiber Technologies, Inc., Billerica, MA) as the shell material. The connector was modified to accept a glass preform, which was used to form the hermetic seal with a stepped index, 100-micron core optical fiber. After seal formation, a standard alumina ferrule SMA connector was glued to the unsealed end of the optical fiber and both connectors were polished using standard techniques.

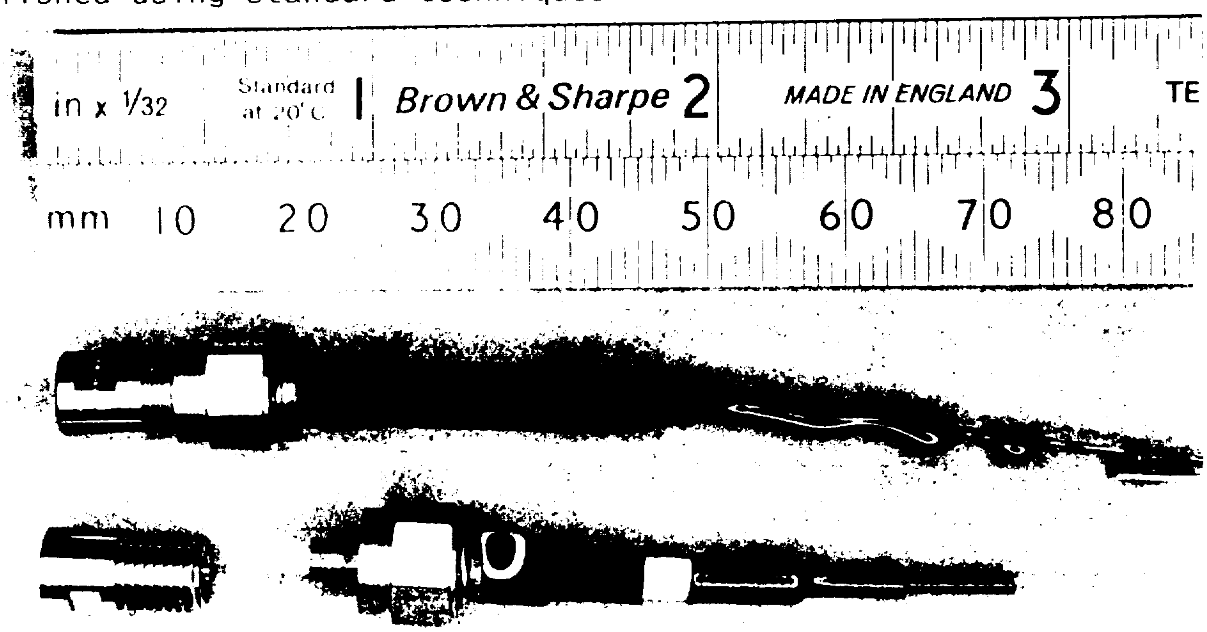

Figure 2 - An example of a "full-up" Direct Fiber Placement Device (top), assembled from a loaded shell (bottom left) and a sealed Direct Fiber Placement component (bottom right).

Several of the Direct Fiber Placement test components were loaded with either Ti/$KClO_4$ or CP (2-(5-cyanotetrazolato) pentaamine cobalt III perchlorate) doped with carbon black. The CP/carbon black units were loaded with 17.0 mg of powder pressed to a density of 1.7 g/cm^3, while the Ti/$KClO_4$ units were loaded with 20.0 mg of powder to a density of 2.0 g/cm^3. The components were ready for firing after a closure disc was welded onto the output end of the unit. Firing tests were performed using the test setup shown in Figure 3. The components were ignited using a 500-mW, 10-ms (5.0-mJ) laser diode pulse. All of the components functioned and the test results for two of these components are shown in Figure 4.

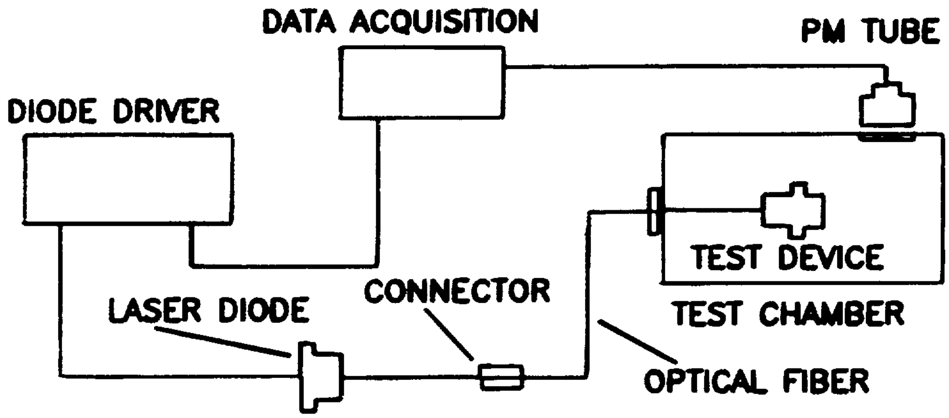

Figure 3 - Test setup used in determining the function times of the fabricated devices.

Figure 4(B) was obtained on a CP/carbon black loaded component, and shows a very short function time of ~0.2-0.4 ms. Figure 4(C) was obtained on a Ti/$KClO_4$ loaded device and it exhibited a longer function time of ~1-ms. The results obtained on the components were encouraging since the units functioned during the initial part of the laser diode pulse. The difference between the function times obtained on these two components is related to CP/carbon black having a lower laser ignition threshold value than Ti/$KClO_4$. An energetic material's laser ignition threshold value is a function of its heat capacity, thermal conductivity, and several other physical and chemical properties.

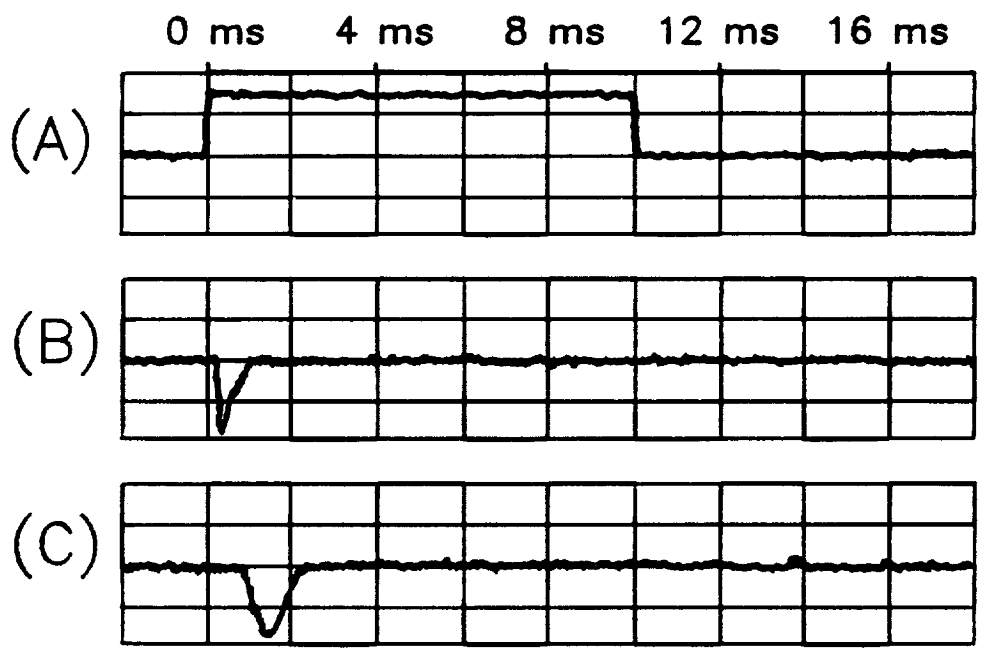

Figure 4 - Traces of the laser diode pulse (A), the photodetector signal obtained from a hermetic, CP/carbon black-loaded, Direct Fiber Placement component (B), and from a hermetic, Ti/$KClO_4$-loaded, Direct Fiber Placement component (C).

Fiber Pin Components

Fiber Pin components (Figure 1) are fabricated using short lengths of optical fibers or "pin(s)," which are meant to function in the same general manner as the metal pins they replace. Some advantages of Fiber Pin devices are: 1) the "pin(s)" are optical fibers, which mean they act as waveguides, 2) there is no fiber pigtail that may be damaged during handling, and 3) these devices can be designed to withstand high pressures. The latter is true since the pressure spike applied to the "optical pin" during functioning is low due to the fiber's small cross-sectional area. The main disadvantage of these components is that they must be mated with an external connection to the energy source. This is not trivial since the alignment of two small diameter optical fibers (typically less than 200 microns) may be difficult, especially when one of the fibers is sealed within a device. Connections of this type also typically result in inherent signal losses due to angular and axial fiber misalignments and reflections.

An example of a high-strength Fiber Pin device is shown in Figure 5. This component was fabricated by first fixturing, a stainless steel shell, a glass preform, and an optical fiber. After fixturing, hermetic seals between the glass and the shell and between the glass and the optical fiber were formed by heating in a furnace to the appropriate temperature. The main difficulty in fabricating these components is obtaining crack-free, hermetic seals due to the large mismatch in the coefficients of thermal expansion between the stainless steel shell and the optical fiber. The formation of crack-free, leaktight seals is made possible only by the careful selection of the sealing glass and by the precise control of the time-temperature furnace parameters.

Figure 5 - Fiber Pin device (maximum O.D. ~1.27-mm) that was fabricated with a short length of optical fiber (small spot in the glass) instead of a metal pin.

Fiber Pin components have been prepared by loading with ~93 mg of $TiH_{1.65}/KClO_4$ powder pressed to a density of 2.2 g/cm^3. These components were designed to be high-strength devices capable of withstanding the high pressures produced during the ignition of the pyrotechnic without self-destructing. This type of function testing has been designated as Zero Volume Firing. Zero Volume Firing is an extreme overtest performed by threading the component into a pressure block that contains a calibrated transducer. Figure 6 shows the test setup used in the Zero Volume Firing tests, which were performed by driving the laser diode output to ~700-800 mW for a pulse length of 10-ms (7-8 mJ). Figure 7 shows the results of a Zero Volume Firing test obtained on one of the loaded Fiber Pin components. The top trace in Figure 7 shows the time duration of the laser diode pulse (10-ms), while on the bottom is the pressure trace. The maximum pressure obtained with this

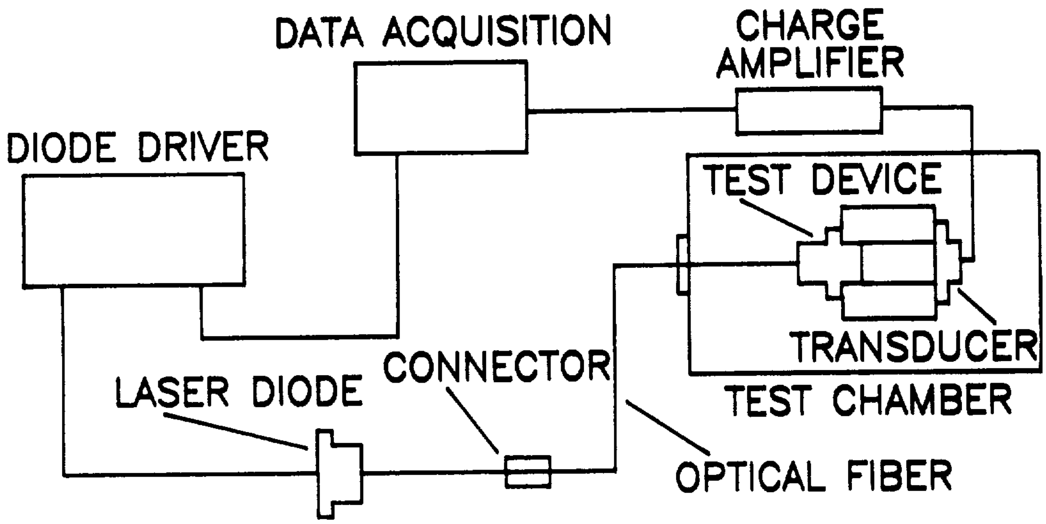

Figure 6 - Test setup used in determining the pressure output of fabricated high-strength test components.

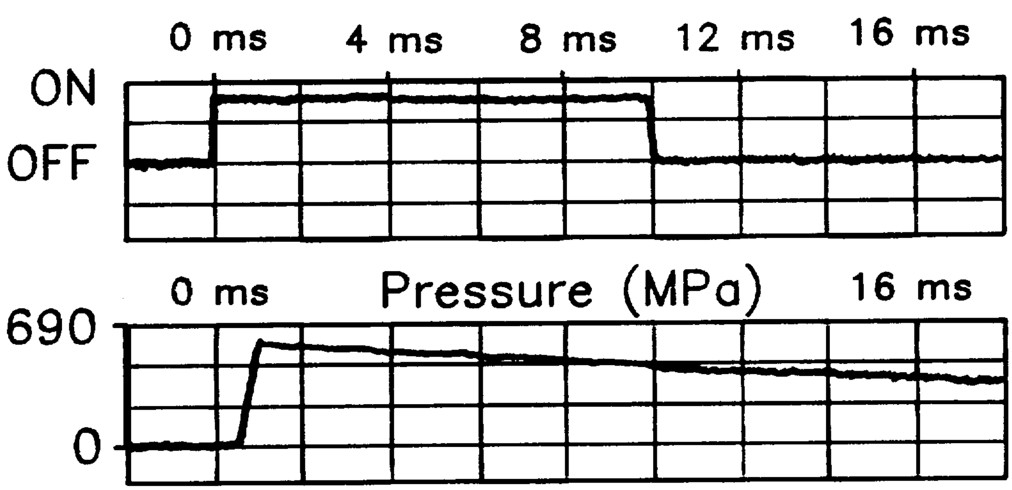

Figure 7 - Traces of the laser diode pulse (top) and of the transducer output (bottom) obtained on a $TiH_{1.65}/KClO_4$ loaded, hermetic, Fiber Pin device.

stainless steel device was ~550 MPa (~80,000 psi). The trace shows that the component successfully held the pressure without failure. The slight decrease in the pressure trace as a function of time is due to the cooling of the reaction products and not due to any pressure release by the component.

Transparent Window Components

Transparent Window components (Figure 1) are classified as components that contain a transparent window sealed within the structural member or shell. The window has typically been fabricated out of either sapphire or glass. The selection of the window material is based on a number of considerations including: 1) the index of refraction of the window material, 2) the required strength of the component, and 3) the thermal expansion relationship between the window and the shell.

Window components have one very significant characteristic which makes them very attractive for application in laser-ignited components. This advantage is that the window diameter is many times larger than that of the connecting optical fiber. Therefore, there are minimal concerns about aligning the connecting optical fiber to the window. This eliminates signal losses due to misalignment. However, window components have basically the same limitations as Fiber Pin devices in that they have inherent losses due to reflections at the fiber-to-window interface. In addition, window components have the added disadvantage in that the window does not act as a waveguide; hence, the incident light will diverge as it travels through the thickness of the window. The magnitude of the divergence is a function of window thickness (which determines the strength of the window) and the window's index of refraction. Therefore, the design engineer must accept a trade-off between the amount of beam divergence that is acceptable to insure the functioning of the component and its required strength.

An example of a window component that has been developed jointly with the U.S. Navy is shown in Figure 8. This component is a hermetic, stand-alone, laser-ignited deflagration-to-detonation transition (DDT) detonator which was originally designed for use with the Navy's Laser Initiated Transfer Energy Subsystem (LITES) [16-18]. The detonator uses the secondary explosive HMX doped with 3% carbon black as the ignition charge and undoped HMX as the transition charge. In all of the development tests conducted the detonator has successfully functioned as designed and has remained completely intact after detonation. These tests were accomplished using a pulse from a Nd:YAG laser through a 1-mm optical fiber, even though other optical fiber/laser combinations could be utilized. As designed, the detonator has been determined to be capable of successfully effecting detonation transfer in a number of configurations after being initiated from a laser source.

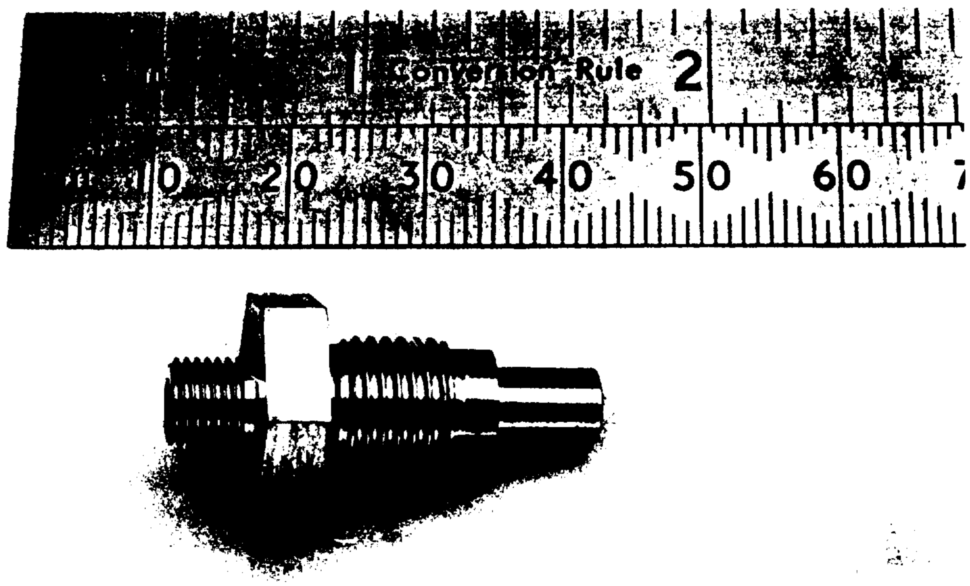

Figure 8 - Hermetic, window, laser-ignited all-HMX DDT detonator.

SUMMARY

It has been demonstrated that the fabrication of hermetic, laser ignited, pyrotechnic and explosive components is possible. This new technology based on a laser/optical fiber or window combination in place of bridgewire(s) and pin(s) can readily be adapted to various engineering requirements. Several novel processing techniques have been developed for fabricating these devices that have been shown to exhibit the required strength and hermeticity to ensure the successful functioning of the device. Examples of several types of laser-ignited devices have been fabricated and tested using a variety of pyrotechnic and explosive materials. These function tests have confirmed that reliable, high-strength devices can be produced. The results illustrate that there are no fundamental reasons why laser ignited components should not be considered for future designs of pyrotechnic and explosive components.

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