MATERIALS, FABRICATION, AND ASSEMBLY TECHNOLOGIES FOR ADVANCED MEMS-BASED SAFETY AND ARMING MECHANISMS FOR PROJECTILE MUNITIONS

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ABSTRACT

This paper outlines the U. S. Army's technical progress toward realizing a miniature, inexpensive, mass-producible micro-electro-mechanical systems (MEMS)-based mechanical safety and arming (S&A) device with embedded compatible micro-scale firetrain for projectile munition fuzes. It illustrates the significant advances in MEMS S&A design simplification, MEMS metal fabrication, and automated micro-assembly technology. These advances have taken place since a June 2005 feasibility demonstration of MEMS S&A in a 20-mm high-explosive air-burst (HEAB) munition for the developmental Objective Individual Combat Weapon (OICW).

1. INTRODUCTION

The U.S. Army Research, Development, and Engineering Command (RDECOM)-Armament Research and Engineering Center (ARDEC) is applying micro-electro-mechanical systems (MEMS) technology to produce significantly smaller, safer and less expensive mechanical safety and arming (S&A) devices for munition fuzing systems than have been possible before. The baseline mechanical S&A systems in use today often consist of sizeable housings, gear escapements, pivots, discrete explosive devices such as detonators and piston actuators, and explosive barriers. Some of today's S&As require safety waivers because they utilize "stored energy" to effectuate arming. Under the RDECOM MEMS S&A Manufacturing Technology Objective (MTO), the Army is bringing four leading-edge technologies to bear on the problem of reducing the cost and volume of S&As for projectile munitions to improve lethality through larger payloads (explosives or electronics) and affordability. These leading edge technologies consist of: 1) Highly-safe, wafer-based mechanical MEMS-based S&A designs, 2) High-aspect-ratio (HAR) metal MEMS fabrication and replication technology, 3) Micro-scale firetrain (MSF) technology, and 4) Automated assembly, including inspection, micro-assembly, micro-explosive loading, and packaging of MEMS and MSF parts and sub-assemblies.

Mechanical S&As typically utilize the high-amplitude, sequenced events of tube launch, for example transient launch setback acceleration in tube and high-speed spin stabilization, to inertially actuate the arming mechanism. Inputs that don't match launch, such as random tumble, vibration, or drop-impact, are generally not capable of causing the mechanism to arm – this is the safety aspect of the S&A. For this architecture, arming consists of moving a meaningful amount of explosives, usually a transfer charge embedded in a MEMS arming slider, from a position that is out-of-line with all other explosive components, to a position where it is in-line with them and completes the firetrain on the MEMS scale.

This paper outlines critical advancements in design and manufacturability of MEMS S&A as applied to 25-mm medium caliber and large caliber applications. This capability, when mature, will significantly enhance soldier lethality by making safer and more reliable weapons affordable, with less weight, and larger warheads or improved guidance or target sensing. The basic MEMS-based mechanical S&A technology can apply not only to medium- and large-caliber munitions, but also to mortars, submunitions, rockets, and mines.

2. DISCUSSION

2.1 MEMS-Based S&A Architecture

To perform the safety and arming functions of a mechanical safety and arming (S&A) device, the MEMS-based S&A must incorporate at least two independent safety locks, each of which can prevent unintentional arming of the S&A. The mechanical action of the S&A mechanism serves to control the disposition of a critical

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firetrain element (transfer charge) between a safe and an armed position.

It was necessary to develop a miniaturized firetrain that can be moved from a safe (out of line) to an armed (in-line) position by a MEMS-sized S&A mechanism.

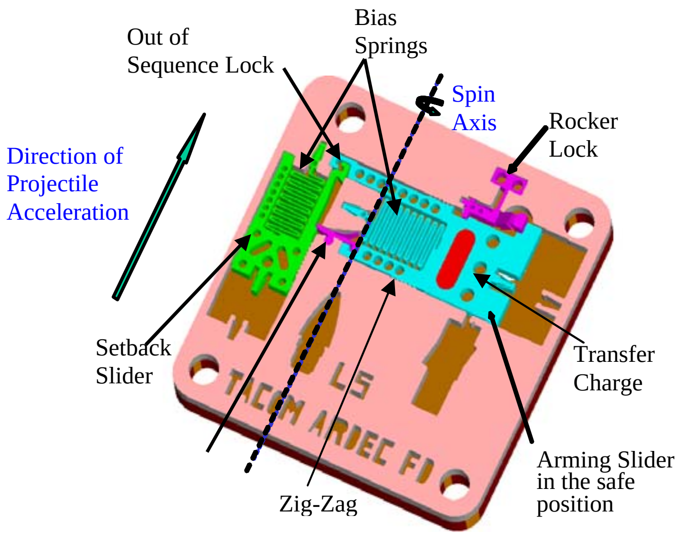


Figure 1: MEMS S&A design in the safe position.

Figure 1 shows the basic design of the inertial-mechanical logic for a MEMS mechanical S&A device. The MEMS S&A consists of a setback slider with a pre-tensioned spring, a setback lock on the arming slider that the setback slider can release, an arming slider, and a command actuator rocker lock, all moving about on a wafer substrate and confined to operate within tracks imposed by a "frame" that is attached to the substrate. The arming slider controls the position of an explosive-train element called a transfer charge that is held out-of-line with the firetrain until arming occurs. The donor and receiving charges that communicate with the transfer charge are above and below the S&A frame, respectively.

The arming sequence is briefly explained as follows (Robinson, et al., 2005)

1. Launch setback acceleration drives the setback slider aftward against spring tension, slowed by following a zig-zag track, to where it latches at the bottom of its track. This motion automatically disengages the out-of-sequence lock, and a feature on the slider's right arm removes and disengages the setback lock lever from the arming slider;
2. While the S&A is under significant forward acceleration the arming slider is frictionally held in position by its zig-zag track. After tube exit, centrifugal acceleration drives the arming slider to the right against spring tension, until stopped temporarily by the left arm of the rocker lock. This short motion removes a portion of the arming slider that was under the raised portion of the rocker lock enabling it now to be rotated by the command piston. After safe separation of the weapon from the gun, a pyrotechnically driven micro-piston, located in a cover plate (not shown) is activated by the fuze circuit (external to the S&A) to push downward on the raised right arm of the rocker lock. This forces the opposite left arm upwards, out of engagement with the arming slider.
3. With continued spin acceleration the arming slider moves right, working against safety-biased spring tension, and latches, putting the transfer charge in the armed position. Added safety (the ability to reject non-launch inputs) is obtained through the requirement that these locks must all be operated in the proper sequence.

Notice that if the command rocker actuates prematurely, or if spin is not present, or if there is insufficient setback, the system either stays safe or fails safe. This basic mechanical logic complies fully with the standards of fuze design and safety. The system is shown post-launch with components deflected to the armed position in figure 2.

As a result of full motion of the arming slider, an insensitive explosive charge, the transfer charge, is moved to a new location lined up with a receptor charge below and a donor charge above, at opposite ends. This completes the initiating firetrain. However, for this to work, the S&A must move a meaningful amount of explosives, and must provide explosive confinement. High-aspect-ratio (HAR) metal MEMS processes, such as LIGA (German acronym for lithography, plating and molding) are capable of producing the needed geometries.

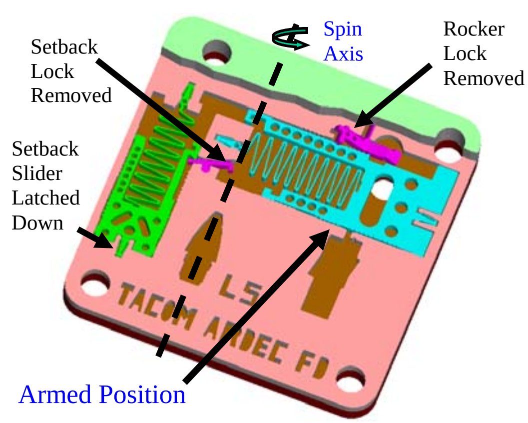


Figure 2: MEMS S&A design in the armed position.

2.2 High-Aspect-Ratio (HAR) Metal MEMS

Traditional wafer-based LIGA uses synchrotron radiation (X-Ray) and a patterned absorber mask to expose a thick PMMA (poly-methyl-methacrylate) resist, which is subsequently developed and plated into, then planarized and released to form polished, micro-resolution parts. Early prototype MEMS S&A assemblies were made using this method to fabricate precision parts (sliders and locks) and frames that were discussed above. LIGA was chosen initially, over brittle MEMS materials such as silicon, to capitalize on the material ductility, mass, and explosive confinement provided by nickel. Parts fidelity and ruggedness was sufficient to demonstrate overall concept (MEMS S&A) feasibility in a weapon-firing live-ammo demonstration in June, 2005. An example of a LIGA-formed MEMS S&A frame, with micron resolution and flat sidewalls, is shown in Figure 3. This fabrication process, however, is highly specialized in that it requires a high-powered, collimated X-ray source for mold formation. In addition, the number of these sources is quite limited and the high cost of building new ones makes it prohibitive for the mass production of HAR MEMS S&A devices.

Several technical approaches were investigated as part of the ARDEC-managed MEMS S&A MTO, with the objective of developing a method to produce microparts for pennies apiece and to pave the way for increased throughput (thousands of units per day). The approaches centered on cutting out the high-cost x-ray synchrotron from the process flow and developing ways to produce replicate parts from a high fidelity LIGA master. Table 1 shows the MTO down-selection rating criteria for various prototype-manufacturing process technologies.

The MTO down-selected process technologies chart is based on physical features, mechanical performance, producibility, cost, and parts presentation. The requirements were derived from a Voice of the Customer (VOC) analysis. In a technology investigation and downselect completed 1QFY06, the most promising technologies were identified as UV-LIGA and powder metal injection molding (PMIM), with micro-die casting of aluminum and zinc as a close third as shown in Table 1. UV-LIGA is inexpensive compared to X-ray LIGA, and recent advances in the technology are yielding single- and multi-layer techniques to produce high-accuracy, vertical side-wall parts of extremely high quality. PMIM creates molded metal parts using a nano-particle slurry mixture injected into a LIGA-produced reusable precision micro-mold master. (Heaney, 2004)

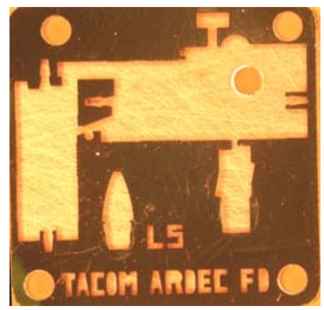


Figure 3: X-ray LIGA HAR MEMS S&A frame with fine feature fidelity and straight side walls

Fabrication Technology Areas	Evaluation Criteria - Requirements							Total Weigting Factor
	High Aspect Ratio (10%)	High Resolution (10%)	Vertical Sidewalls (10%)	XY Resol. & Repeatability (10%)	Corrosion & Expl. Confinment (10%)	Producibility Process Scalability (20%)	Cost $ per million (30%)	
DRIE/Bosch (silicon)	0.3	0.9	0.3	0.3	0.1	0.2	0.9	3
X-ray LIGA (metal)	0.9	0.9	0.9	0.9	0.9	0.2	0.3	5
Plastic Injection Molding	0.9	0.1	0.3	0.3	0.1	0.6	2.7	5
Hot Embossing (plastic)	0.9	0.3	0.3	0.3	0.1	0.6	0.9	3.4
UV LIGA (metal)	0.9	0.9	0.9	0.9	0.9	1.8	0.9	7.2
Sinter Metal Powders	0.3	0.1	0.3	0.3	0.3	0.6	0.9	2.8
Powder Metal Injection Molding	0.9	0.3	0.9	0.3	0.9	1.8	2.7	7.8
µ Die Cast (Al & zinc)	0.9	0.1	0.3	0.3	0.1	1.8	2.7	6.2

Table 1 - MTO Down-selected Process Technologies Chart: Using the Quality Function Deployment (QFD) and Analytical Hierarchy Process Methods.

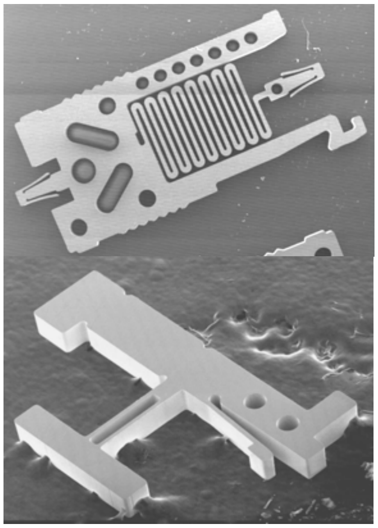


Figure 4: UV-LIGA setback slider (top) and rocker lock (bottom, prior to bending), showing fine feature fidelity and straight side walls, Axsun Technologies, Inc.

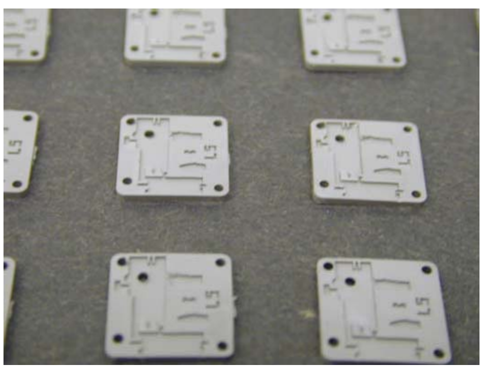


Figure 5: Powder metal injection molding of frames, Pennsylvania State University.

Excellent progress has been achieved in developing both of these processes. Figures 4a - 4b show the HAR metal MEMS S&A parts and frame with fine feature fidelity and smooth, straight side walls using UV-LIGA. Figure 5 shows the results of PMIM fabrication of S&A frames.

Based on the MTO down-select evaluation of various process technologies, this study determined that UV-LIGA and PMIM technologies are capable of reproducing the desired geometries for large volume production. Additional development will be carried out in FY07-08 to create inexpensive replicates to further reduce device costs and optimize manufacturing processes.

2.3 Micro-Scale Energetics

2.3.1 Micro-Scale Firetrain

A new miniaturized explosive train was developed in parallel with the MEMS mechanical S&A. The micro-scale firetrain (MSF) replaces current macro-scale explosive components and explosive trains that are too large in dimension and energy output to remain safe when integrated with a safety interrupter of micron or sub-millimeter dimensions (e.g. MEMS S&A). There were three hurdles to overcome with the MSF:

1. Most secondary explosives qualified for use down-line of the safety interrupter (arming slider) will not work because their critical diameter and run-to-detonation length values are too great for implementation in MEMS S&A. Even primary (sensitivie) explosives used before the safety interrupt often behave in a non-ideal fashion when configured at such small dimensions.
2. It is difficult to load explosives into MEMS-scale shapes and sizes
3. Initiating a detonation in components at this scale requires a bridged header and package much smaller than is conventionally available for military use.

Figure 6 shows the innovative MSF baseline design that was generated by the ARDEC team (Robinson, 2006).

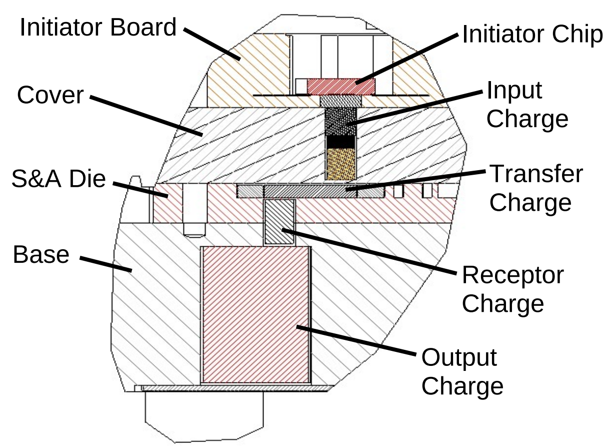


Figure 6: Baseline Design, MEMS MSF

The following are innovative features of this design:

- This is a true “out-of-line” configuration utilizing a moveable transfer charge, so if the safety interrupter is removed, the input and receptor charges are not aligned, resulting in enhanced safety.
- Part of the input charge, and all of the transfer-, receptor- and output-charges are composed of pressed RSI-007 secondary explosive powder. This is a CL-20 based molding powder that was developed under a Navy SBIR contract with

Reynolds Systems Inc. in Middletown, CA as a booster explosive for use in high voltage slapper detonators. Extensive testing and characterization efforts proved that this is the only known explosive qualified for use in Army weapon systems that possesses the necessary critical diameter, run-to-detonation distance, sensitivity, and loading characteristics to make it compatible with the previously mentioned requirements of the MEMS-scale safing and arming environments. (Chan, 2003)
- Initiation for the MSF is provided by a small off-the-shelf thin-film bridge chip that is manufactured in large quantities and low cost for the auto airbag industry by Vishay Inc.
- Conventional primary explosives are used in the initiator board as a bridge spot charge in the MSF input charge to build the detonation front.
- The output charge provides output similar to the M100 detonator.

Since establishment of the baseline design, an extensive series of parametric developmental tests were performed to optimize specific areas of the MSF which displayed less-than-optimal functional reliability in previous testing. Varying parameters such as explosive material, density, diameter, and increment length, as well as housing confinement material, and barriers/gaps between adjacent components, resulted in an optimized design that demonstrated 20 out of 20 successful detonations in laboratory experiments. Testing to validate the improvements to the baseline MSF prototype design consisted of static laboratory function and safety tests and ballistic launch and function field tests.

A critical part of meeting the MIL-STD-1316 requirement for fuze safety is that the S&A device prevent propagation of any explosive reaction beyond the safety interrupter in the case of an inadvertent initiation of the detonator section. (DOD, 1991). With the small size of the MEMS S&A, the explosive components are now in much closer proximity, making safety more difficult. Fully-out-of-line safety tests were performed that proved the barrier effectiveness with the S&A in the fully safe state. Penalty out-of-line safety tests were performed where both the input and transfer charges were initiated in the out-of-line position to verify that the receptor and output charges still remain in good condition. In these tests the receptor charge still remained in excellent condition.

As a final safety check, "progressive arming" tests were performed to quantify the safety of the interrupter as a function of its arming position. Results of this test provided further evidence of a robust safety design.

The baseline MSF design uses explosive components formed by consolidating powder into pellets, much like traditional components are made, just on a much smaller scale. This kind of production is labor intensive and time-consuming. In 2005 as part of the MEMS S&A MTO program, Dr. B. Fuchs and A. Wilson of RDECOM ARDEC, formulated a brand new secondary explosive composition called EDF-11 and developed and demonstrated that this slurry mix could be directly "written" into MEMS-scale cavities and subsequently initiated as part of a high explosive firetrain. See Figure 7. They are currently working on a method to slurry-load primary explosives. (Wilson, 2006)

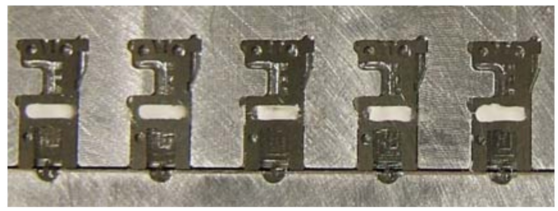


Figure 7: Direct Write Loaded arming sliders

2.3.2 Command Micro-Actuator

The subject MEMS-based S&A architecture calls for an electrically-initiated command micro-actuator (CMA) to physically remove the second lock from the arming slider to permit mechanical arming of the S&A. The command signal comes from the fuze circuit, external to the S&A, once criteria for safe separation from the launch platform are met. This CMA takes the form of a "rocker lock" that engages with the arming slider, to stop its forward motion until a signal from the fuze circuit pyro-electrically pops a piston downwards on the opposite end of the rocker, forcing that end down. As a result, the first end rocks up and out of the way of the slider, freeing it to arm. The micro-piston is located in the over-structure, or cover, of the MEMS layer. Structural, dynamic, and reaction kinetics analyses were used to arrive at the design shown in Figure 8.

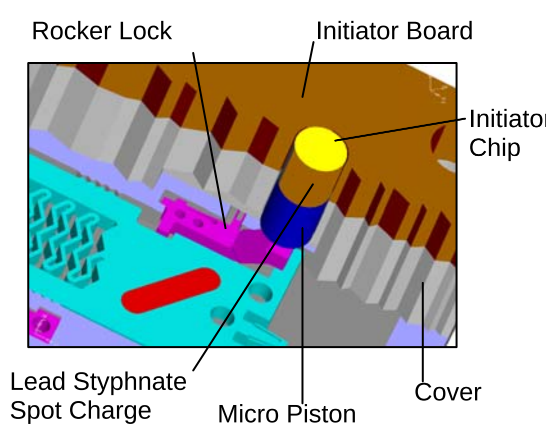
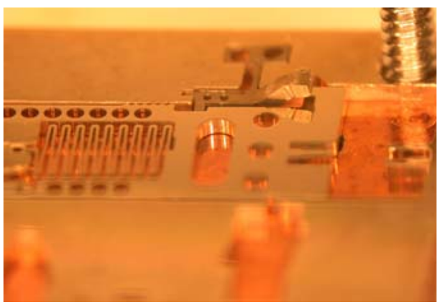
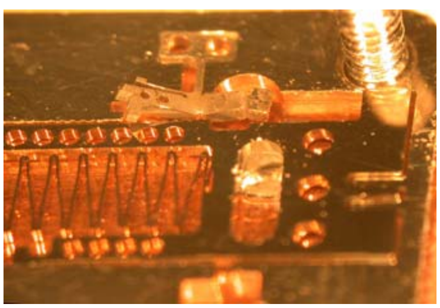


Figure 8: MEMS Command Micro-Actuator

Developmental testing of the CMA examined functional reliability and included ignition of the pyrotechnic, generation of gas, movement of the piston, and movement of the rocker locker mechanism enough to release the arming slider. Over 100 actuations during laboratory and ballistic testing, including a weapon testing, demonstrate that the CMA is a reliable design and the prototype systems operate in a repeatable, robust manner. Technical issues that were overcome to achieve a successful design included: preventing reaction gases during function from crossing over to the MSF and causing premature initiation; realizing a 3-D formed micro-part using an inherently 2-D fabrication process, this included developing cutting-edge layered electroplating technology; and cold-forming planar electroplated parts to achieve bends and out-of-plane surfaces while retaining material properties and device functionality. Figure 9 shows the CMA rocker-lock position before and after actuation by the pyrotechnic gas-driven piston. A simpler rotary type actuator is currently being developed.



CMA rocker-locker, pre-test



Actuated rocker-locker, post-test

Figure 9: CMA Developmental Testing Results

2.4 Automated Micro-Assembly and Inspection

Because of the wide variety of systems to be integrated and component sizes and packaging requirements, the high-volume micro-assembly of MEMS devices generally requires customized processes and equipment. Though existing pick-and-place equipment vendors sell solutions for the micro-electronics industry, these off-the-shelf turn-key solutions have proven incompatible with the unique requirements of a MEMS S&A assembly. Much of the research work on MEMS assembly focuses on wafer-level approaches. This is incompatible with our explosive integration requirements. For many micro-assembly applications customized solutions like highly precise rigid pallets and fixtures are required. (Feddema, 1999)

For this application, a machine-vision, automated micro-assembly (MVAM) system was developed to integrate the manufacture, assembly, and automated inspection of the MEMS S&A. Such automation is essential for cost goals and high throughput to be achieved. A system was developed and demonstrated in June 2006 that exhibits micron-accuracy, force control, and electrostatic discharge control with custom manipulators to handle the MEMS parts and explosive elements.

The system leverages heavily on pick-and-place manipulation techniques developed for the surface mount electronics, but it also performs somewhat unusual tasks, such as to pre-tension springs and test effectiveness of latching. This automated system will greatly reduce assembly time and process variability when compared with manual assembly techniques used earlier in the program. It will increase throughput from greater than 1 hour for each manual S&A assembly to less than 1 minute for the automated system.

Figure 10: Automated micro-assembly cell currently under ARDEC evaluation

The MVAM system uses optical parts recognition to identify and inspect randomly-strewn MEMS mechanism parts in a Petri dish, orient and kit them, then work from kitted parts to a complete S&A assembly. This system approach starts with individual programmable work cells that can be ganged to complete a range of operations, including explosive loading of nearly-completed S&As.

Figure 10 shows the type of micro-assembly cell currently being investigated by the ARDEC MEMS team. This manufacturer claims 1-micron axis resolution in 3 orthogonal directions, with axes repeatability +/- 3 sigma of 4 micron. In-plane chuck speeds are rated at 1 m/s.

The process utilizes machine vision for part-sorting, kitting and inspection, both pre- and post-assembly, see Figure 11. This system has the capability for automated video metrology and data archival between stations for traceability and 100+ percent inspection. The equipment has a programmable 0.1 to 50-N force table for sensing touch-down and force applied

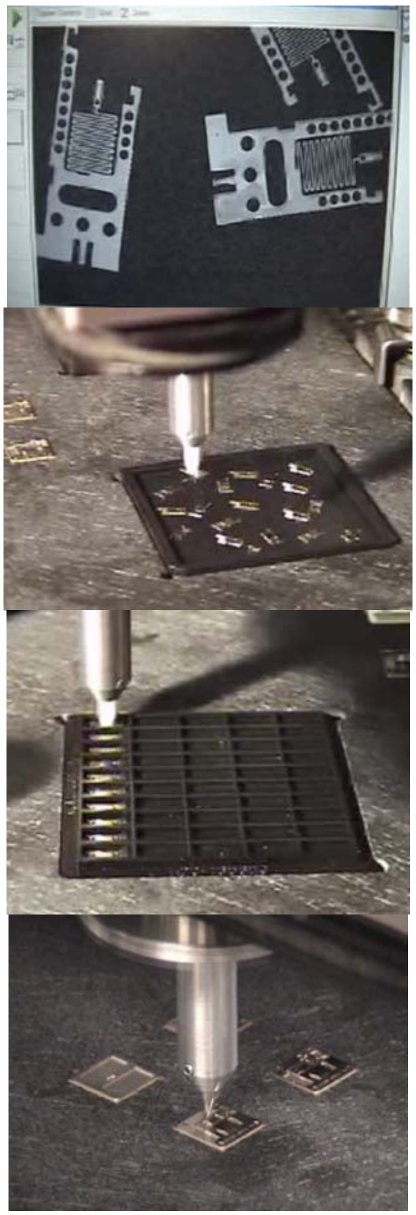


Figure 11: Inspection, Sorting, Kitting, and Assembly Process of Arming Sliders

through the pick-and-place head. The MEMS S&A design requires pre-biasing of the springs, so the chosen equipment must also be able to manipulate components in the plane of the MEMS layer. Analysis indicates that the assembly goal of 100 S&As per hour is achievable with this equipment by the end of FY07.

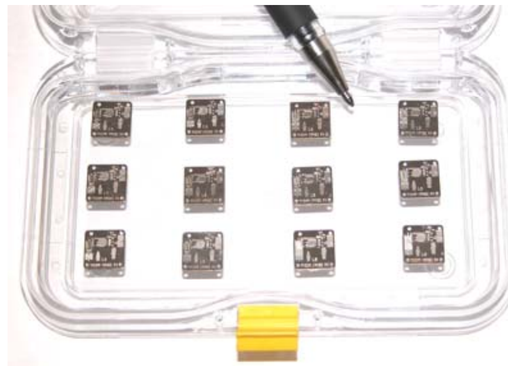


Figure 12: Twelve MEMS S&A mechanism assembled via the micro-assembly process.

At the start of this development effort, two major difficulties needed to be overcome to make the MVAM process a reality: 1) manipulation of the micro-components, and 2) automated handling of micro explosives. The pick-and-place approach currently under development has already shown the feasibility of assembling micro-scale components. Figure 12 shows twelve MEMS frame layers with four components placed via automation. The MEMS frame shown is 10mm on a side. Additional work has to be performed to develop handling procedures for the micro-scale fire-train elements. Procedures for force and electrostatic discharge control to ensure safe handling of sensitive explosive features will be developed. Requirements for these procedures were considered during equipment selection and this approach looks promising. After the micro-components and explosive are in place, the whole S&A system-level assembly must be stacked up to include the initiator board, cover and MEMS layer. This stack must be fastened in a robust, cost effective manner. Optimization of the MVAM approach will accelerate the pace at which the advantages of MEMS-based fuzing can be realized by materiel developers and in turn be fielded to the warfighter as an enabling fuzing technology.

CONCLUSIONS

The new MEMS-based S&A architecture exploits a unique combination of advances in high-aspect-ratio metal MEMS fabrication technology and high-volume micro-mold replication methods and materials, advances in micro-scale firetrain materials and dispensing techniques, and automated micro-assembly and inspection to achieve higher reliability, improved safety, lower volume and the potential for lower cost for mechanical

S&A systems for munition fuzes. These advances in MEMS S&A manufacturing technology are being accomplished entirely with on-shore sources to pave the way for a planned 2008 technology transition to the U. S. Army's Office of the Program Manager for Soldier Weapons. Ultimately these technologies will benefit the warfighter through increased lethality and greater functionality by shrinking the S&A size to allow for more payload, power, and guidance electronics. Furthermore a smaller S&A will enable greater flexibility for distributed integrated fuzing and the integration of additional sensors and fuze functions.

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REFERENCES

Chan M., G. Hennings, G. Meyers, J. Pakulak, and R. Reynolds, 2003: Qualification of CL-20 Explosive (RSI-007) for Application in Explosive Foil Initiators, Naval Air Warfare Center Weapons Division TP 8548.

Department of Defense, 1991: Design Criteria Standard, Fuze Design, Safety Criteria for, MIL-STD-1316D.

Feddema, J.T. and T.R Christensen, 1999: Parallel Assembly of LIGA Components, *Tutorial on Modeling and Control of Micro and Nano Manipulation, IEEE Int. Conf. On Robotic and Automation*, Detroit, Michigan.

Heaney D. F., T. J. Mueller and P A. Davies, 2004: Mechanical Properties of Metal Injection Molded 316l Stainless Steel using both Prealloy and Master Alloy Techniques, *Powder Metallurgy* Vol. 47 No. 4, pp. 1-7.

Rasmussen, J., J Krafcik, 2005: MTO MEMS S&A Development Program: UV-LIGA Fabrication Process, Axsun Technologies Inc, Final Report.

Robinson C. H., R. H. Wood, T. Q. Hoang, M. R. Gelak, D. Hollingsworth, 6 Jun 2006: Micro-Scale Firetrain for Ultra-Miniature Electro-mechanical Safety and arming Device, *U.S. Patent No. 7055437*.

Wilson, A. D., 2006: Explosive Ink Formulation for the Loading of MEMS, National Defense Industrial Association Fuze Conference.