INTEGRATED QUALITY ASSURANCE PROGRAM FOR THE HYDRA-70 SOLID ROCKET MOTOR

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INTRODUCTION

The Hydra-70 uses small solid rocket motors, which are produced in large numbers. It is used by all branches of the US armed forces and those of several other countries. A research and development program was initiated in 1994 which had the objective of improving the quality of the motors. The motors use solid fuel grain and the effort reported in this paper focuses on providing motors with higher reliability in terms of performance and safety, and at the same time achieving a significant reduction in inspection costs.

The complete QA program for the Hydra-70 rocket motor considers all aspects of the life cycle. It considers motors at the time of manufacture and those in the stockpile. The analysis consideres the manufacturing process, defect analysis, physical and chemical testing, current real-time radiography (RTR), analysis of effects of aging, live firings and the use of ultrasonic testing. This paper reports aspects of the ultrasonic element of the program.

BACKGROUND

In the US the majority of inspections applied to ordnance and pyrotechnic devices employ radiography of some type. Radiography can be very effective; however there are some types of geometry and forms of defects to which it is less sensitive. The inspection of the grain used in the Hydra-70 has been performed using real-time radiography, where the part is rotated during the inspection. An alternative is to employ film x-ray, but this requires

Review of Progress in Quantitative Nondestructive Evaluation, Vol. 17
Edited by D.O. Thompson and D.E. Chimenti,, Plenum Press, New York, 1998

exposures at a series of angles that are time consuming. In addition the length of the item requires that two films are used; all these factors combine to increase inspection costs.

The application of ultrasonic inspection techniques is not novel. Ultrasonics has been employed to inspect propellants and explosives since at least the 1960's [1,2,3]. Ultrasonic waves have been used in fundamental modeling and experimental studies. For example, they have been used in multi-layered, cylindrical systems to determine the visco-elastic properties of the propellant [4]. And, ultrasonic waves have also been used in the implementation of various inversion schemes for defect sizing [5]. Various studies have considered the application of ultrasonics to solid rocket motor propellant and experimental work has been performed to quantify the effects of aging on propellant properties [6,7].

MANUFACTURING PROCESS

The grain is manufactured as an extrusion from a thermo-plastic filled polymer. The item is then cut to length, machined to size, end-caps are attached and the item is wrapped. The wrap is fabricated in place and applied with a solvent that causes formation of a thin solid layer that is also connected to the end-caps. The final grain is heat treated and cured. The grain is inspected while being manipulated through a helical motion using real-time radiography (RTR). With the current RTR, bore features in the grain make images difficult to read. Some types of defects are hard to detect reliably, even when using image reversal and double reading.

The grain can suffer from a variety of potentially significant defects. These include fissures, voids, poor consolidation, with or without additional bursts and voids, wrap defects and foreign material. Defect analysis has shown that radial-linear defects are considered to be structurally most significant. It is these features which are most difficult to see with RTR. Alternate inspection modalities were therefore investigated.

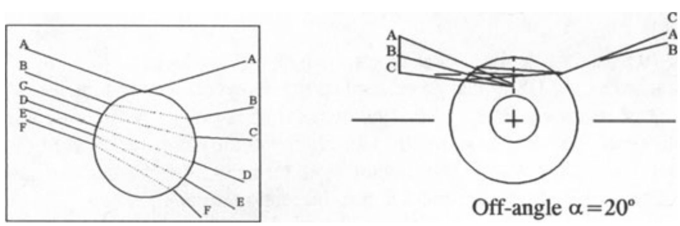

Fig. 1. Examples of ray tracing analysis.

ANALYSIS FOR THE IMPLEMENTATION OF ULTRASONICS

The implementation of ultrasonics, in immersion, on a grain to give a very reliable inspection is not simple. The grain is basically a cylinder, where the central bore has structure. A mix of practical trials and analysis was performed so that an initial inspection transducer configuration could be developed. A range of ray-tracing was performed to enable optimal inspection configurations to be identified. Examples of ray tracing are shown as Fig 1. Of particular concern was the inspection of the web region. Ray tracing for the case of a focused transducer set to inspect this region is shown.

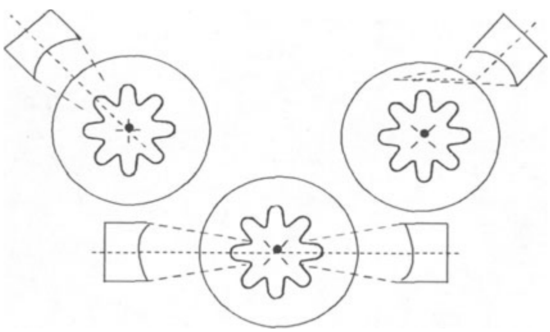

Fig. 2. Ultrasonic immersion inspection transducer configurations.

On the basis of the ray tracing and a series of initial experiments three basic inspection configurations were implemented. These use a transducer in pulse-echo set normal to the bore, a pair in transmission through the bore and a transducer set to inspect the web. These configurations are shown in Fig 2. The high attenuation in the material requires the use of a low-frequency transducer (1 MHz). The inspection configurations were then optimized to give a preferred transducer diameter, focal length and orientation/standoff for each of the three basic configurations

The inspection technique was implemented using a 4 channel ultrasonic system which was constructed to a specification developed by Indian Head, NSWC. The system presents data in the form of color C-scan images, an example of which is shown in black and white as Fig 3. This is an image for a good motor. The image for a bad motor is shown as Fig. 4. Channel 1 is pulse echo into the web; Channel 2 is pulse-echo normal to the bore; Channel 3 is the through-transmission normal to the bore and Channel 4 is pulse-echo to the web, near the bore.

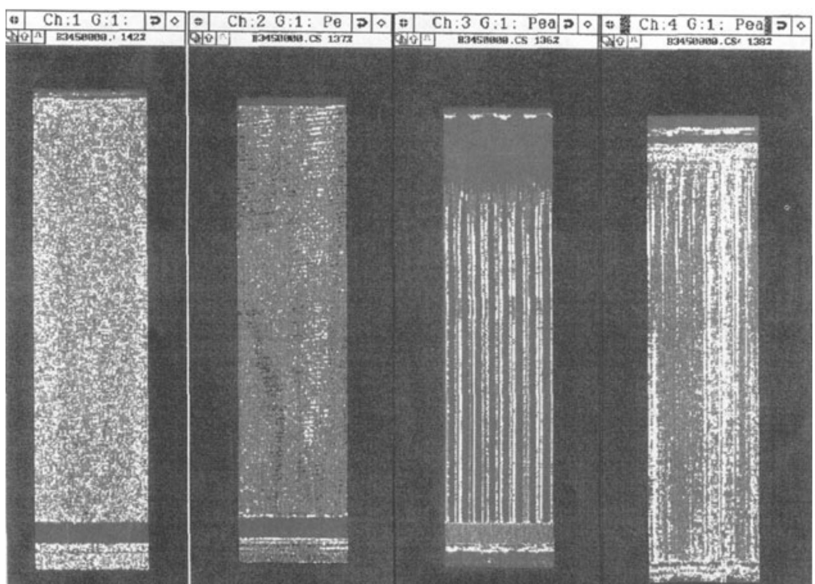

Fig. 3. Example of an ultrasonic image for a good grain.

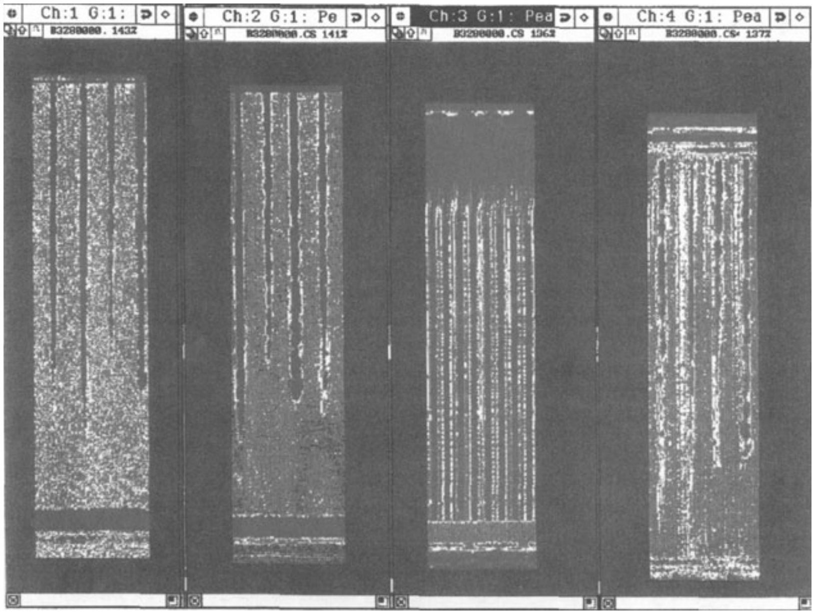

Fig. 4. Example of a grain with linear defects.

On the basis of data from previous RTR inspection, destructive testing, structural analysis and experience with live firings a set of inspection criteria were defined. A helical scan plan was implemented, with the step sizes being pre-set to meet the defect detection requirements. The sizing of defects seen in the images is based on pixel counts. The ultrasonic gate settings are used to minimize bore indications and also wrap indications. When necessary, the A-scan data can also be used by the operator to investigate the defect characteristics in further detail.

QUALIFICATION

A qualification plan for ultrasonic was then developed [8]. As a part of the activity a detailed evaluation protocol was designed based on the draft MIL-STD 1823 [9]. The basic Probability-of-Detection [POD] characteristic seeks to consider system performance in the light of the basic parameters (I) system detection limit (set by system and the physics of ultrasound-defect interactions), (ii) an Accept-Reject criteria and (iii) a critical flaw size (determined independently). These parameters are shown on the idealized POD characteristic given as Fig 5, together with the 95% confidence bound.

A grain is approximately 30 inches in length and 2.75 inches in diameter. This can be considered as 30 independent axial segments and at each ring there are at least 3 circumferential elements. For 100 grain there is therefore a trial population with the ability to accommodate small defects in 9,000 potential defect locations. This provides an adequate number of independent "good" and "bad" tests for - good and defective regions, which can be considered to be independent.

The protocol was established to use 100 grain, with geometrical dimensions and material properties which were representative of the population intended to be inspected. Grain were selected that had defects which were identified and a series of RTR inspections performed to provide a reference defect data set. Inspections were then performed and the dimensions of all defects recorded. The full analysis of test data to enable probability of detect [POD] to be determined is presented in several places [10]. For the DRI activity the POD analysis was implemented in the form of an EXCEL spreadsheet, and a Fortran code.

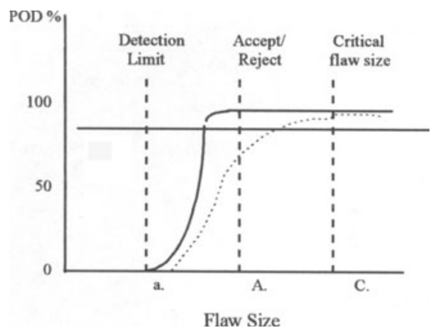

Fig. 5. System capabilities - probability of detection and confidence bound (95%).

The initial reference data set of defect dimensions used were those given by RTR. It was seen that the ultrasonic inspection was detecting at least 20% more defects than RTR. Also there were potentially significant differences - the ultrasound was detecting the presence of more linear defects than the RTR.

The performance of ultrasonics, using the best available radiographic sizing as the reference was evaluated [11]. The resulting POD characteristic is shown as Fig 6. For all defects where data were available the POD was effectively 100%, and the confidence bound for the 95% confidence level was excellent.

The data were then reviewed using the best available ultrasonic defect sizing (performed as part of an Engineering Study) as the reference. The performance of RTR compared with ultrasonic testing for small defects was assessed and the POD characteristic shown as Fig 7 obtained. For those defects which appear to be foreign material or small voids the POD was good. The apparent 95% POD at zero defect size is an artifact of the data set; the POD must go to zero at zero size. A cause of concern was the reduction in the confidence bound for larger defects. This is a cumulative characteristic and will get worse if larger defects are being missed. This was investigated further.

It was found that for the population of linear indications identified by ultrasonics that a significant number of these were missed by RTR. The performance of RTR for defects in the trial population which exhibited these features was evaluated and the resulting POD characteristic is shown as Fig 8 [12]. It is seen that a 50% POD is not achieved until a linear feature has a length of about 120 mm and that 100% POD is not obtained even when the feature is the full length of the grain. The 95% confidence bound is given as zero.

An analysis of all available data shows that one type of defect, thin linear indications, are not reliably detected by RTR. From a structural analysis it is these features which are considered to be structurally most significant.

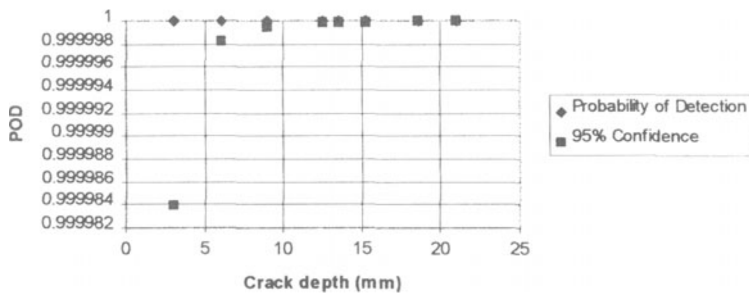

Fig. 6. POD for ultrasonic data vs. radiography.

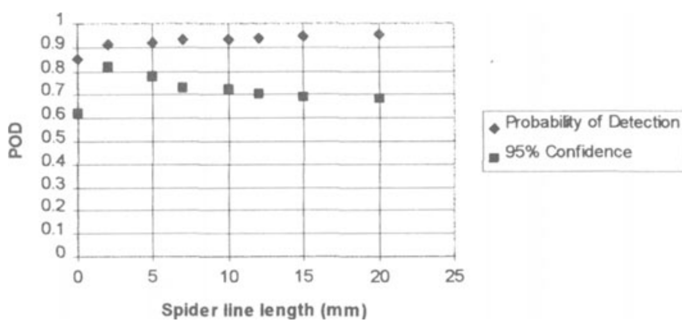

Fig. 7. POD RTR all types of features (showing data for small features) 2mm assumed detection limit.

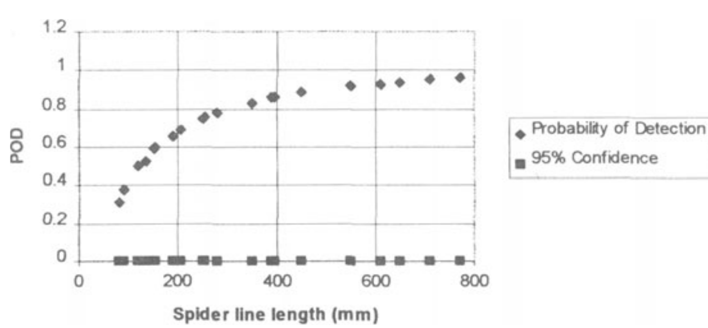

Fig. 8. POD for linear features using RTR, with 2.5mm assumed detection limit.

COST SAVINGS

Time required for a radiographic examination is 6 minutes per item. The time required to inspect a grain using a fully automated ultrasonic inspection system has been shown to be 1 minute. This factor of six reduction in item inspection time results in significant cost savings.

CONCLUSIONS

The ultrasonic technique developed and implemented under this program is detecting critical flaws with a higher POD than real-time radiography (RTR). The RTR implementation used is found to be least sensitive to the most critical defect type, those which are thin linear features.

Ultrasonic inspections provide a significant reduction in inspection costs. The resulting data are much easier to read and the reading has been automated.

The new approach of using ultrasonics, with state of-the-art ultrasonic instrumentation, is providing product which has improved quality and higher reliability, and this is achieved at a lower cost.

ACKNOWLEDGEMENTS

This program was funded by the U.S. Army Industrial Operations Command, Rock Island, IL.

The authors acknowledge the contributions made to the numerous members of the Hydra-70 Inspection Team, at the Indian Head Division, NSWC. The contributions made by members of staff of Alliant Tech Systems, in particular those at the Radford Army Ammunition Plant who are participating in the Hydra-70 program. The radiographic defect sizing performed at Concord Naval Station, CA. The contributions made by the staff of Sonix and Matec who have supplied the ultrasonic systems used in the program.

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