FAILURES OF THE M72A2 LAW ROCKET SYSTEM

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ABSTRACT

Over a period of several years, the M72A2 LAW Rocket has experienced a number of malfunctions traceable to failures of either the rocket motor closure or the rocket motor itself. Both of these components are made of 7001 aluminum alloy heat treated to the T6 temper, an alloy known to possess low fracture toughness properties and also to be highly susceptible to stress corrosion cracking. The role of stress corrosion in a number of these malfunctions is discussed, and the remedies chosen to alleviate each problem as it occurred are described. Comparisons are made between the mechanical and physical properties of material from production lots manufactured during different time periods, and comments are made regarding factors that would appear to be contributing to the on-going stress corrosion problem.

INTRODUCTION

The M72 LAW system was developed in the early 1960's as an individual anti-tank weapon used extensively in Army and Marine Corps units. The system consists of a self-contained lightweight shoulder-fired launcher and a high explosive anti-tank (HEAT) rocket (Figure 1). The rocket is made up of the warhead, joined through a closure assembly (which houses the fuze) to an aluminum rocket motor. When fired at 70°F, the burning propellant develops a chamber pressure on the order of 600 psi which propels the rocket from the launcher with a muzzle velocity of about 450 feet per second.

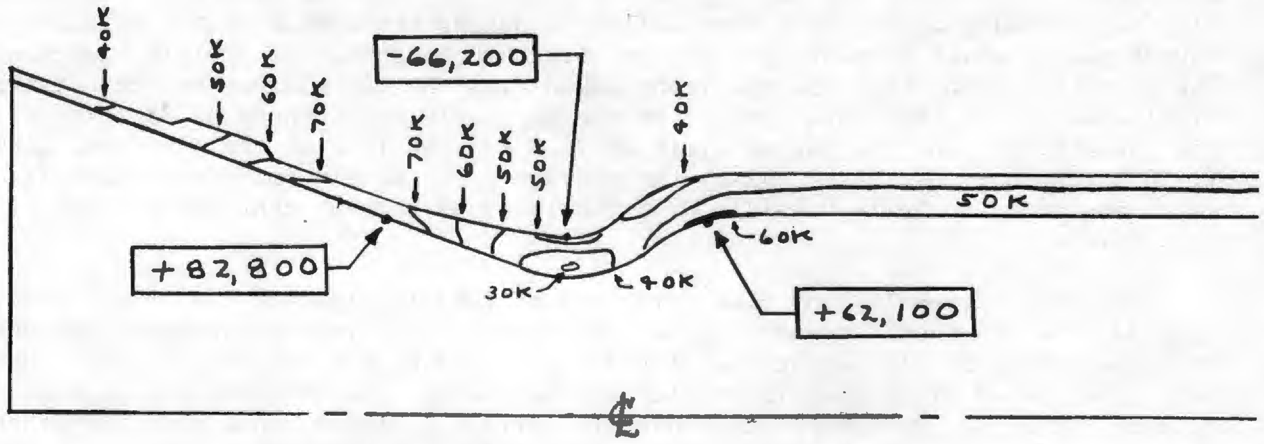
From very early in its history and continuing to the present time, the LAW has experienced a series of problems, some as the result of deficient engineering practice on the part of the manufacturer, but most stemming from inadequacies in the mechanical and physical properties of the aluminum alloy used in the rocket motor and closure. The aluminum alloy used in both of these components is 7001-T6, an age hardenable alloy developed by Harvey Aluminum in the mid 1950's to provide an alloy with higher mechanical properties than any other commercially available alloy of aluminum. Typical properties of 7001 are compared in Table 1 with the properties of other aluminum-zinc-magnesium alloys, all heat treated to the T6 temper (i.e., the maximum strength condition). At the time it was developed, the claim was made that corrosion characteristics of 7001, including resistance to stress corrosion, were comparable to the other high strength 7xxx series alloys.

The strength requirements imposed by the rocket motor design adopted for the LAW mandated the selection of 7001-T6 as the motor material. Figure 2 presents the results of a finite element stress analysis of the LAW rocket motor during launch, showing a maximum effective stress of 83,000 psi occurring in the throat

Figure 1. The M72A2 LAW system.

Table 1. TYPICAL TENSILE PROPERTIES OF 7XXX ALUMINUM ALLOY EXTRUSIONS

	YS ksi	UTS ksi	Elong %
7001-T6	84	92	5
7178-T6	78	86	5
7075-T6	72	80	7
7079-T6	70	79	7



66MM LAW ROCKET MOTOR BODY - AFT SECTION

EFFECTIVE STRESSES

Material - 7001 - T6 Aluminum
Yield Strength - 84,500 psi
Internal Pressure - 9,100 psi
Exit Pressure - 1,050 psi
Acceleration - 4,000 G's

Figure 2. Finite element stress analysis of the LAW rocket motor during launch-effective stresses.

area of the rocket nozzle. Of the commercially available aluminum alloys, only 7001-T6 has a yield strength high enough to withstand this level of stress. Unfortunately, at the time when this alloy selection was made, the concepts of fracture mechanics were not widely used, and the potential for catastrophic failure inherent in the use of a material with low fracture toughness and high stress corrosion susceptibility was not adequately appreciated.

What follows is a brief case history of the LAW problems from AMMRC's first involvement through one of the most recent failure investigations. Various data obtained in the course of these investigations and elsewhere will be summarized in an attempt to give insight into the nature of the corrosion phenomena involved.

CLOSURE PROBLEMS

The first series of malfunctions with which AMMRC became involved occurred in the time period around 1970[1], and was traced to a structural weakness in the rocket closure and the warhead/closure joint. There were two types of failures encountered: (1) the closure split longitudinally due to setback forces upon launch and metal parts were expelled from the rear of the launcher, or (2) separation occurred at the warhead/closure joint, sometimes causing premature warhead

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[1] Carr, Frank L., Larson, Frank R., and McElaney, Francis X., *Metallurgical Analysis of the M72 LAW Closure Failure - Part II*, Army Materials and Mechanics Research Center, AMMRC TN 72-2, February 1972.

detonation. Corrosion was not implicated in any of these malfunctions, but extensive mechanical property data were collected during the course of the malfunction investigation which demonstrated the low fracture toughness of 7001-T6 aluminum. The results of many tests of specimens taken from the LAW closure and the statistical analysis of that data showed the average yield strength to be 83.1 ksi with the lower 99 percent confidence limit at 76.8 ksi, well below the specified minimum yield strength of 84.5 ksi. Also, the average plane strain fracture toughness value was found to be 14.0 ksi$\sqrt{in}$ with the lower 99 percent confidence limit at 11.6 ksi$\sqrt{in}$.

With the extremely poor flaw tolerance of 7001-T6 aluminum now in evidence, coupled with its known stress corrosion susceptibility, recommendations were made to replace 7001 in all components of the LAW with a higher toughness alloy. However, because of other factors at play at the moment, the decision was made to retain 7001 in the system but to reduce the stress in the closure and strengthen the warhead/closure joint through the application of a fiberglass overwrap. While this corrective action was effective in providing a solution to the immediate problem of closure failures, it failed to take into account the basic deficiencies of the material and its use elsewhere in the system, with the result that a new series of failures developed less than five years later.

ROCKET MOTOR FAILURES - PART 1

This new round of malfunctions was confined to rocket motors produced by a single manufacturer (hereafter referred to as Manufacturer A). The typical failure signature is illustrated schematically in Figure 3. Upon firing, failure of the

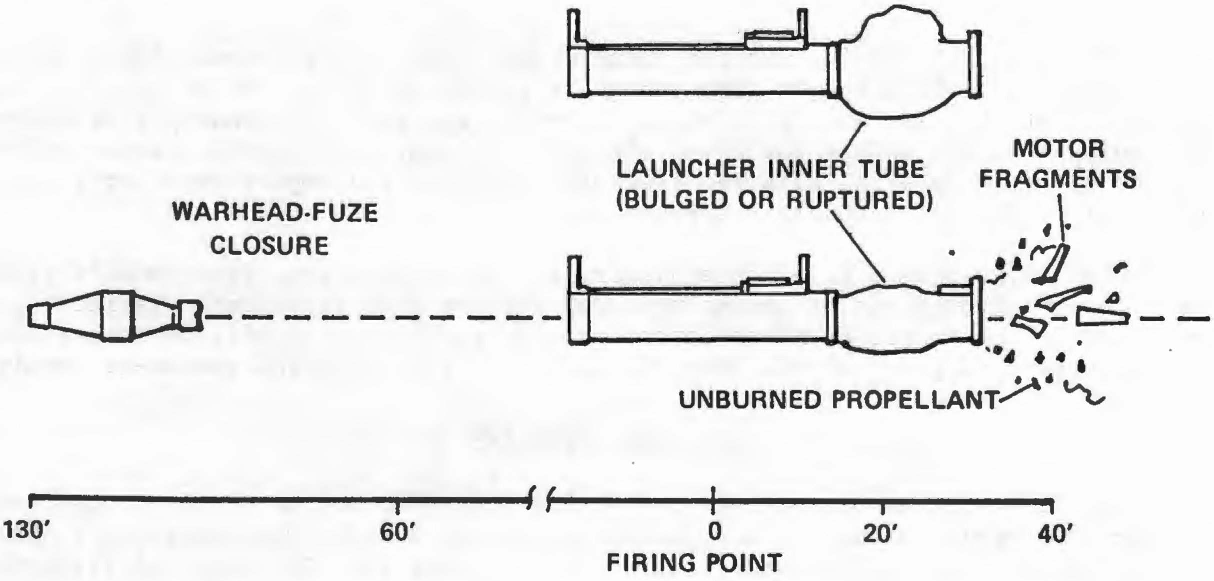


Figure 3. Schematic representation of typical LAW rocket motor malfunction.

rocket motor occurred with little or no rocket travel in the launcher, expelling unburned propellent and motor fragments to the rear and propelling the warhead and closure a short distance forward of the launch point. The launch tube was bulged or ruptured, but miraculously no serious operator injury took place.

Typically, the rocket motor broke into two or three major fragments, as shown in Figure 4, with the primary fracture path running longitudinally the full length of the motor. Following the chevron markings on the fracture surface allowed the fracture path to be traced back to the point of primary origin, which almost invariably was located on the nozzle rim. Secondary fracture origins in the throat of the nozzle were often activated by the bending forces which developed following the initial fracture. Close examination of the fractures showed the primary origins to be stress corrosion cracks on the order of one millimeter (0.040 inch) in depth (Figure 5), which exhibited the intergranular appearance typical of stress corrosion in the scanning electron microscope, as shown in Figure 6. Verification of stress corrosion cracks in the nozzle rim as the operative failure mechanism was obtained by test firings of rockets with machined notches cut into the rim of the nozzle; the failure signature that resulted was identical to the actual malfunctions. It was later demonstrated that the condition leading to the formation of these stress corrosion cracks was most likely introduced by one of the proof tests used as a quality assurance measure during motor production.

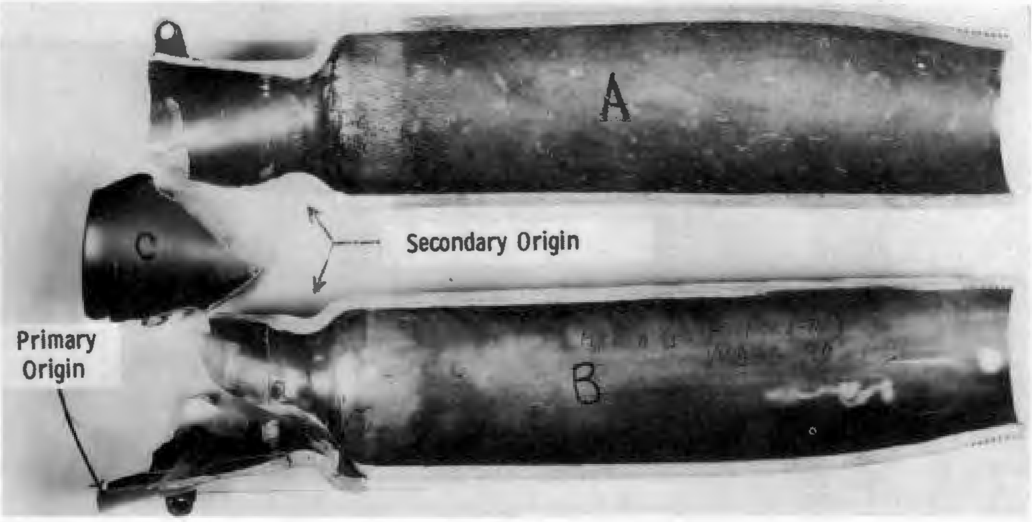


Figure 4. Typical LAW motor failure.

Figure 5. Primary fracture surface in LAW motor failure showing the primary initiation site (Reference 2). Mag. 3.5X

Figure 6. Fracture surface at primary initiation site showing intergranular fracture (Reference 2). Mag. 1500X

Fracture toughness measurements performed on specimens taken from motors of the affected manufacturer produced K_{IC} values as low as 7 ksi$\sqrt{in}$ with the average being 10-11 ksi$\sqrt{in}$. Taking K_{IC} = 10 ksi$\sqrt{in}$ and assuming a stress of 45 ksi (35 ksi launch plus 10 ksi residual stress) a critical flaw depth of 0.3 mm (0.012 inch) was calculated, supporting the contention that the observed stress corrosion cracks were indeed supercritical[2].

2. *Malfunction Investigation Program, Rocket, He, 66-MM:AT, M72 Series (LAW) - Metallurgical Program,* U. S. Army Armament Research and Development Command Report, Pittman-Dunn Laboratory, April 1976.

Again, the situation should have been clear that the basic problem stemmed from the use of 7001-T6 aluminum, a material with very low flaw tolerance and with high stress corrosion cracking susceptibility. Nevertheless, the decision was made to salvage the remaining stockpile by again overwrapping the affected component (this time the rocket motor) with fiberglass. In detail, the fix involved machining a small quantity of material from the nozzle rim to remove any stress corrosion cracks already present, followed by a fiberglass overwrap of both the rim and the throat areas of the rocket nozzle, as shown in Figure 7. The throat wrap was for the purpose of reinforcing the most highly stressed area of the motor and to arrest any cracks which might initiate and propagate from the nozzle rim. The rim wrap was to prevent ejection of metal fragments from the rear of the launcher in the unlikely event of a motor failure. Firing tests of pre-flawed motors showed the wrap to be effective in both these points. The basic deficiencies of 7001-T6 aluminum were still ignored, however, and history was soon to be repeated.

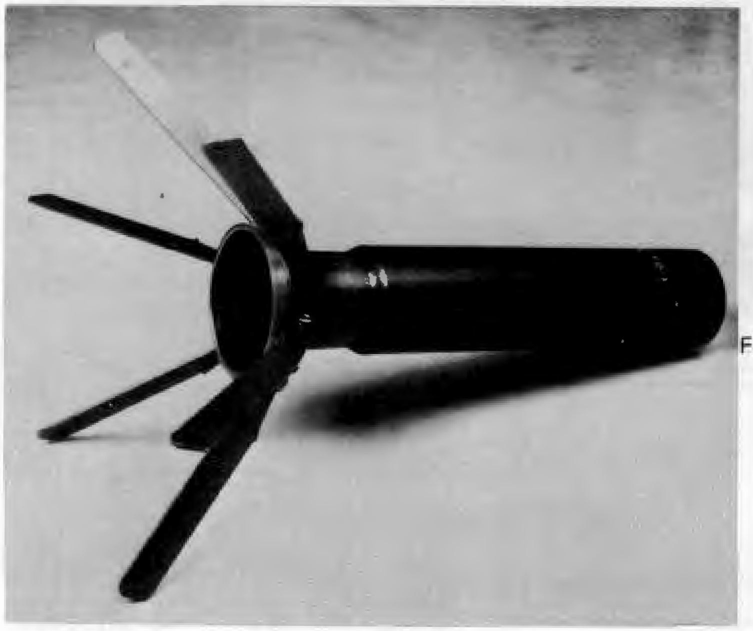


Figure 7. Fiberglass wrapped LAW rocket motor.

ROCKET MOTOR FAILURES - PART 2

In the span of a few weeks in mid 1978 two malfunctions occurred in fiberglass wrapped rocket motors. The failure signature resembled, in most aspects, the signature of the previous motor failures: a few large fragments with a primary longitudinal fracture. Figure 8 shows the motor fragments recovered from one of these malfunctions along with a diagram of the fracture path[3]. The primary fracture initiation site is at point A, the base of the fin slot on the lug rim, rather than at the rim of the nozzle as in the earlier malfunctions. A finite element stress analysis of the wrapped motor had shown that the region of maximum stress would be moved away from the throat of the nozzle to the lug rim by the

[3] Bruggeman, Gordon A., *An Investigation of the Failure of a Fiberglass-Wrapped M72A2 LAW Rocket Motor*, Army Materials and Mechanics Research Center, AMMRC TN 79-2, January 1979.

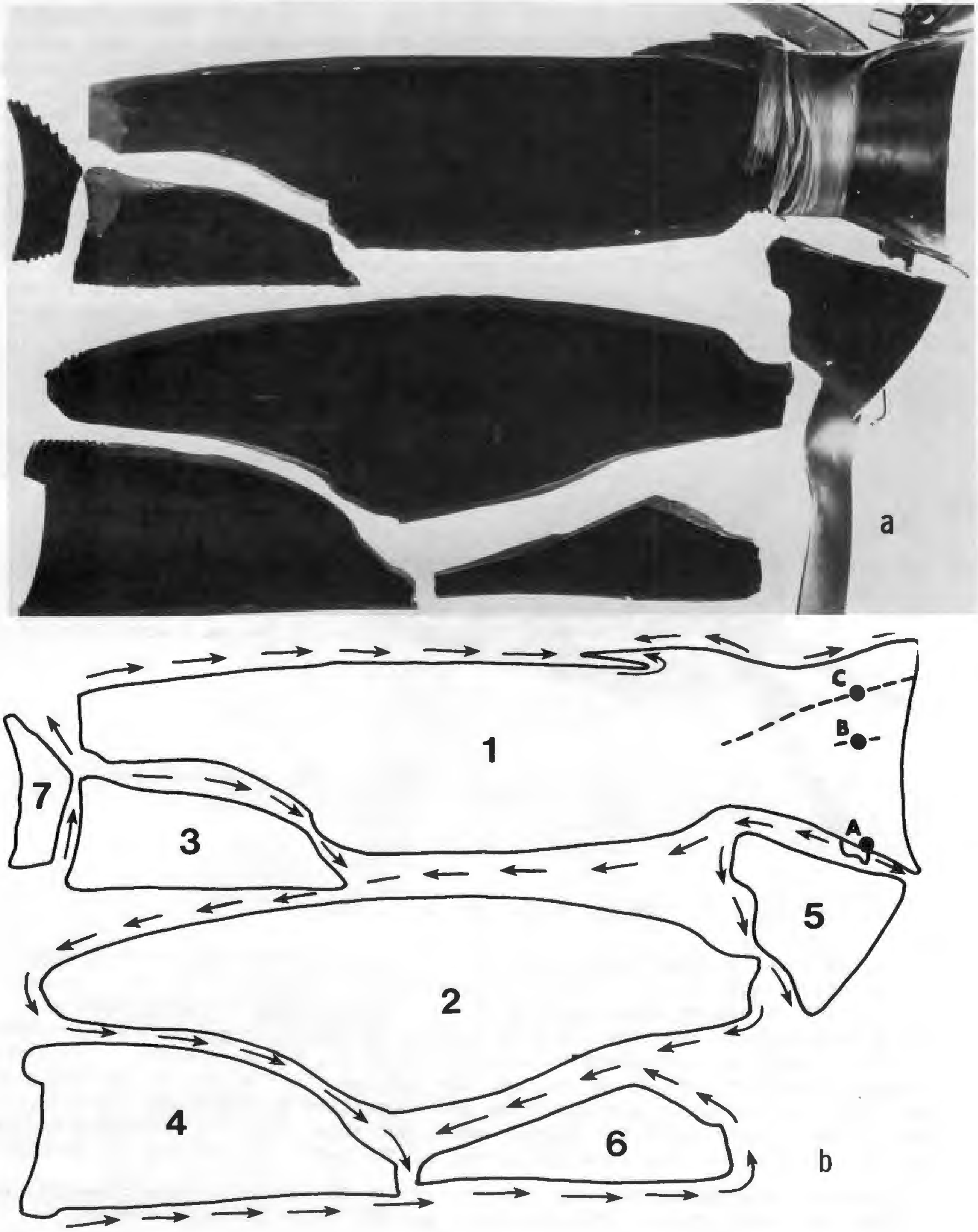
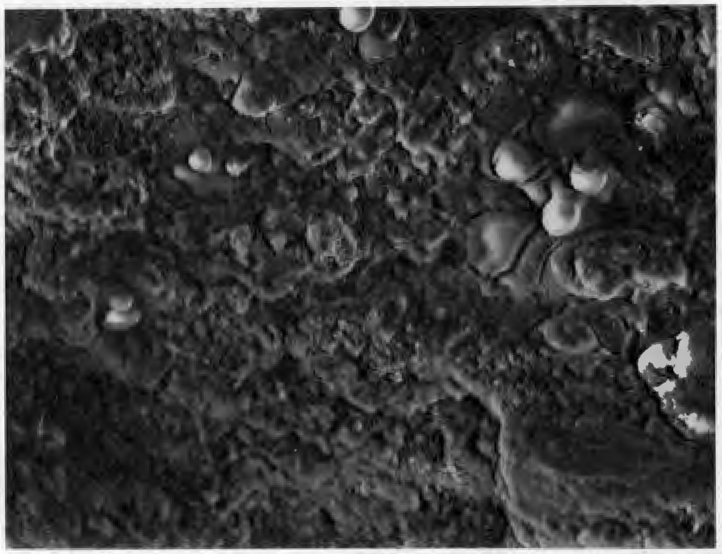


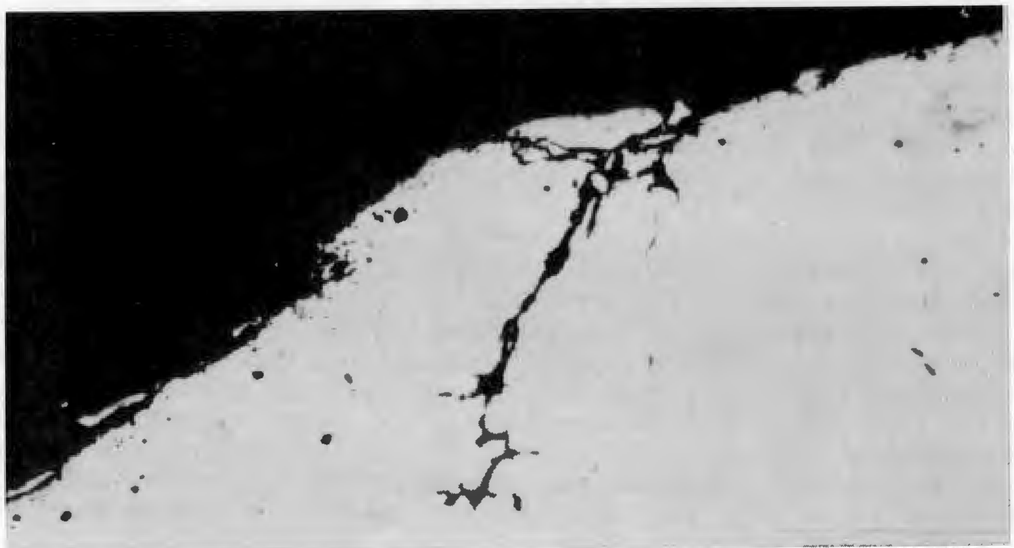
Figure 8. Fragments from fiberglass wrapped LAW motor failure (Reference 3).

application of the fiberglass. Thus the failure of the wrapped motor appears to have initiated at a location near the point of maximum stress. Secondary crack initiation sites were also located in equivalent locations B and C at the base of other fin slots on the lug rim. These secondary cracks were unrelated to the primary fracture and apparently developed independently.

Examination of the fracture surface near the primary initiation point again gave evidence of intergranular fracture and crack branching (Figure 9), suggestive of a stress corrosion failure mechanism. Similar features were observed at the



a. Mag. 500X



b. Mag. 1000X

Figure 9. Primary fracture initiation site in fiberglass wrapped motor failure showing (a) "mudcracking" and intergranular fracture, and (b) crack branching (Reference 3).

secondary crack initiation sites at B and C, as well. However, no pre-existing flaws could be identified. It was speculated that the anodized coating at the base of the fin slots may have been damaged when the fins were moved for the fiberglass wrapping operation, and that this contributed to a later corrosion problem.

One other point of interest was the failure of the throatwrap to arrest the crack propagating from the lug rim, in contrast with what had been demonstrated earlier. Apparently, relaxation of the wrap during long-term storage reduced its crack arresting effectiveness.

DISCUSSION

From the picture of LAW performance thus far presented, it would appear that all LAW systems, regardless of their manufacturer, have been subject to problems of stress corrosion and poor flaw tolerance because of their common usage of 7001-T6 aluminum. Interestingly, this has not been the case. Of three manufacturers involved in LAW production over the years, one has had a far worse malfunction record than the others. Table 2 compares the motor failure rates compiled from several years of firing experience by the three manufacturers. Manufacturer A has clearly had the more difficult time whereas the experience of Manufacturer C has been extraordinarily good. It may be useful to compare various material and process parameters from the three producers to gain insight into the cause of this difference in performance.

Table 3 compares some typical chemical compositions obtained from sample rocket motors of the three producers along with the specified chemistry for 7001. Note that Manufacturer B had used a high zinc version of 7001 aluminum (alloy designation ZG93), but beyond that, there appears to be little in the way of significant differences between the alloys. In recent years, Manufacturer C has chosen to restrict the zinc, magnesium, and copper levels to the lower end of the 7001 chemistry range, to significantly reduce the maximum amounts of iron and silicon, and to place tight controls on the maximum sodium and hydrogen levels. Even without these restrictions, however, Manufacturer C reportedly has had uniformly trouble-free experience. The iron concentrations, often related to poor ductility and a loss in toughness, are no worse for Manufacturer A than for Manufacturer B.

Table 4 summarizes mechanical property data obtained from motors produced by the three manufacturers. With the exception of one data set (i.e., Manufacturer C, circa 1975), all data entries represent the results of from four to eight tests. From a ductility and fracture toughness standpoint, the data from Manufacturer B motors seem the least desirable, with the Manufacturer C (circa 1979) motors showing up the best. More or less as expected, the leaner chemistry of the more recent Manufacturer C motors has had the effect of modestly lowering the strength and raising the ductility and toughness. The mechanical properties of Manufacturer A's motors appear to be quite good and certainly do not reflect the poor firing record experienced by that producer. However, recall that earlier data obtained during the first rocket motor malfunction investigation[2] by the U.S. Army Armament Research and Development Command (ARRADCOM) had produced some K_{IC} values as low as 7 ksi$\sqrt{in}$, so there may be greater variability in Manufacturer A's product than was detected by current tests.

Table 2. COMPARISON OF LAW FIRING EXPERIENCE (MOTOR FAILURE RATE)

Manufacturer	Number Fired	Failure Rate
A	150,000	1/30,000
B	2,000,000	1/400,000
C	800,000	0/800,000

Table 3. CHEMICAL COMPOSITION - LAW ROCKET MOTORS (WEIGHT PERCENT)*

	Zn	Mg	Cu	Cr	Si	Mn	Fe	Ti
7001	$\frac{6.8}{8.0}$	$\frac{2.6}{3.4}$	$\frac{1.6}{2.6}$	$\frac{0.18}{0.35}$	0.35	0.20	0.40	0.20
A	$\frac{(5.0)}{7.9}$	$\frac{2.9}{3.1}$	$\frac{1.8}{2.0}$	$\frac{0.16}{0.24}$	$\frac{0.15}{0.31}$	$\frac{0.01}{0.14}$	$\frac{0.11}{0.40}$	$\frac{0.01}{0.08}$
B (ZG93)	$\frac{7.3}{8.8}$	$\frac{2.4}{2.7}$	$\frac{1.8}{1.9}$	$\frac{0.17}{0.18}$	$\frac{0.24}{0.39}$	0.19	$\frac{0.38}{0.40}$	$\frac{0.04}{0.07}$
C	$\frac{7.0}{7.5}$	$\frac{2.8}{3.3}$	$\frac{1.9}{2.6}$	$\frac{0.11}{0.18}$	$\frac{0.08}{0.13}$	$\frac{0.01}{0.02}$	$\frac{0.10}{0.14}$	$\frac{0.01}{0.03}$
7278	$\frac{6.8}{7.2}$	$\frac{2.7}{3.0}$	$\frac{1.7}{2.1}$	$\frac{0.18}{0.22}$	0.2	0.02	0.2	0.03

*Double numbers represent range; single numbers represent maximum.

Table 4. MECHANICAL PROPERTIES OF LAW ROCKET MOTORS*

Manufacturer	Y.S. ksi	U.T.S. ksi	Elong %	RA %	K_Q ksi$\sqrt{\text{in.}}$
A	81.7 ± 3.1	95.1 ± 2.4	10.0 ± 0.6	21.5 ± 4.9	15.6 ± 2.0
B	84.7 ± 2.8	91.9 ± 1.2	8.0 ± 0.9	11.3 ± 4.3	13.4 ± 1.4
C (circa 1975)	83.1 ± 4.0	98.3 ± 0.3	10.0 ± 0.7	22.3 ± 1.9	15.6 ± 2.4
C (circa 1979)	79.0 ± 2.9	95.8 ± 0.2	11.7 ± 1.6	17.0 ± 5.1	17.5 ± 1.7

*Indicated variability is one standard deviation.

Figure 10 compares the longitudinal microstructures taken from the nozzle area of the three manufacturers' motors. Manufacturers A and C both exhibit recrystallized microstructures whereas Manufacturer B's motors contain a cold worked, unrecrystallized microstructure in this area (partial recrystallization is achieved away from the nozzle). The dark second phase particles in all the microstructures are chromium and iron bearing intermetallics. The maximum size and volume fraction of these intermetallics appears greater for Manufacturers A and C. Quantitative metallography performed on these microstructures tended to confirm this observation with typical data appearing in Table 5. On this basis one might expect that Manufacturer C would have as many problems as Manufacturer A, but this has not occurred.

Since stress corrosion cracks in the nozzle rim would grow only under the influence of a residual tensile stress, the residual stresses in the nozzle were measured by means of the standard X-ray method using a Rigaku MSF Strainflex X-ray unit. The measured hoop stress in the nozzle rim exhibited considerable variability, both between motors and between locations on a single motor, as evidenced in Table 6. The condition of Manufacturer C's motors is by far the most desirable from a stress corrosion standpoint, but one might expect Manufacturer B to have the same SCC problems as Manufacturer A, which has not been the case.

Table 7 summarizes significant aspects of the manufacturing processes used by the three producers, highlighting some of the differences that exist. In so far as is known (not all details are available in their entirety) the major differences lie in the initial preparation of the extrusion slug and in the final aging treatment. Discussing the latter point first, Manufacturer A used a single step aging treatment whereas Manufacturer B employed a two step process. Manufacturer C's aging treatment is not known, but judging from the electrical conductivity values measured on the motor bodies (which can often reflect the state of heat treatment in aluminum alloys) it would seem to resemble that of Manufacturer A. The higher conductivity measured on Manufacturer B motors would indicate a more advanced or complete state of aging (all other things being equal) and might explain the lack of stress corrosion failures, in spite of other factors being unfavorable. The susceptibility of Manufacturer C motors might be expected to approach that of Manufacturer A motors on the basis of this measure of the state of aging, however, which is contrary to the evidence.

The extrusion slugs were prepared differently by all three manufacturers. Manufacturer A purchased air melted direct chill (DC) cast and extruded bar stock which was annealed prior to extrusion of the rocket motors. Manufacturer B vacuum melted an aluminum billet which was then forged into the final extrusion slug. Manufacturer C vacuum melted, DC cast, and homogenized the aluminum billets which were hot extruded to the diameter of the final extrusion slug. What is perhaps the most significant of the process differences (and the one factor which is consistent with the difference in performance) is the fact that Manufacturers B and C melted under vacuum, which will have the effect of lowering the level of residual gases, principally hydrogen, in the melt. In view of increasing evidence concerning the role of hydrogen in the embrittlement and stress corrosion of aluminum[4], reduced hydrogen levels can be expected to have a beneficial effect.

4. Christodoulou, L., and Flower, H. M., *Hydrogen Embrittlement and Trapping in Al-6%Zn-3%Mg*, Acta Met., v28, 1980, p. 481-487.

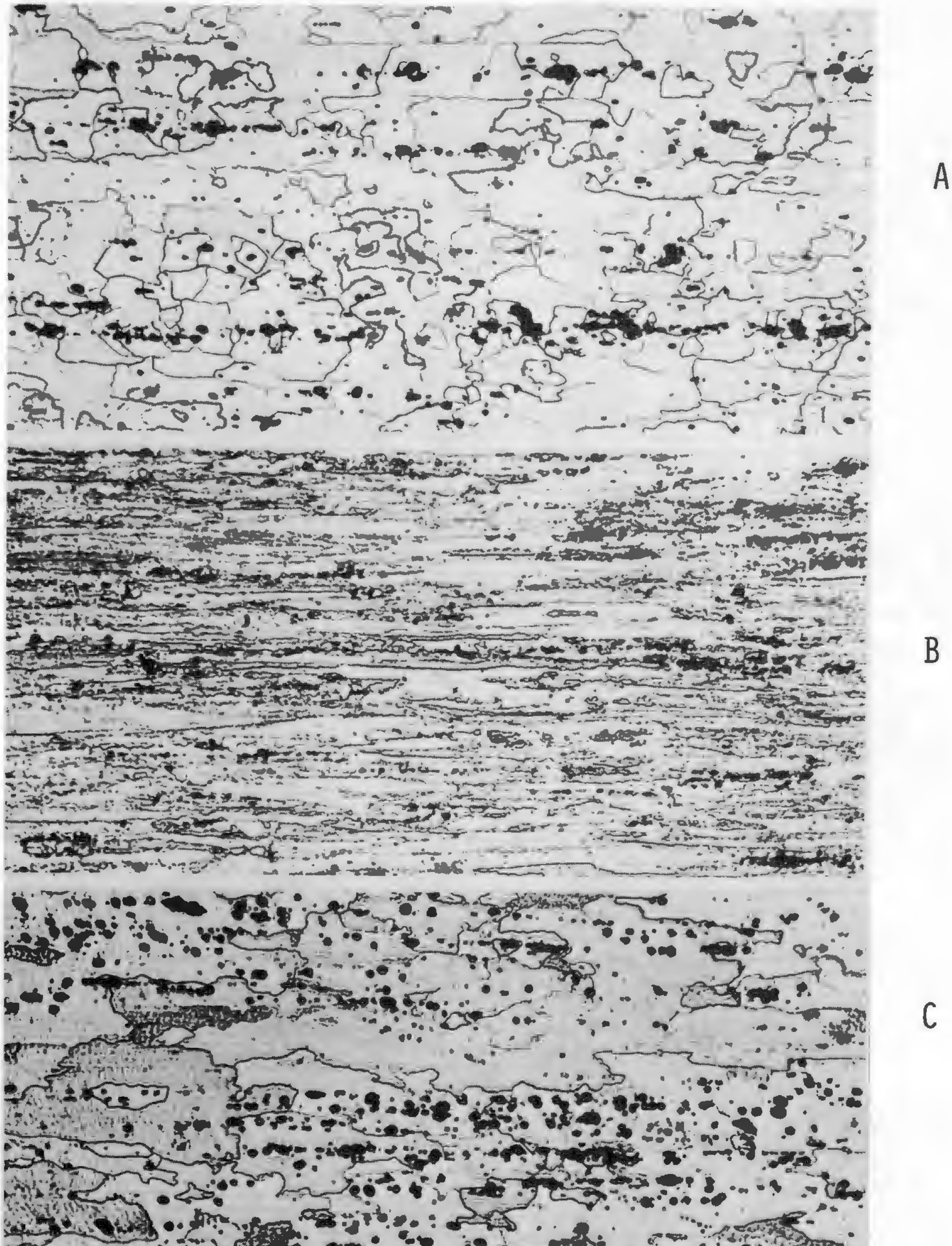


Figure 10. Typical longitudinal microstructures in the nozzle area of motors produced by the three manufacturers. Mag. 200X

Table 5. MICROSTRUCTURAL ANALYSIS OF DISPERSOID PHASE

Manufacturer	Volume Fraction	Maximum Diameter (Micrometers)
A	0.05-0.09	9.1
B	0.08-0.10	6.4
C	0.07-0.16	8.5

Table 6. RESIDUAL STRESSES AT THE NOZZLE RIM IN LAW ROCKET MOTORS

Manufacturer	Residual Hoop Stress
A	9 ksi Compressive to 20 ksi Tensile
B	6 ksi Compressive to 33 ksi Tensile
C	0 to 5 ksi Compressive

Table 7. DIFFERENCES IN MANUFACTURING PROCESS

	A	B	C
Melting	Air	Vacuum	Vacuum*
Condition of Extrusion Slug	DC Cast, Extruded, Annealed	Forged	DC Cast, Homogenized, Extruded
Solution Treat 30 min. at 870°F	X	X	X
Water Quench Temperature	RT	RT	RT
Age	24 hrs. at 240°F	3 hrs. at 250°F & 3 hrs. at 325°F	?
Conductivity % IACS	29.3	32.9	29.5

*Na and H controlled to low levels.

It is not possible, nor is it the intent here, to draw conclusions concerning the relative importance of various metallurgical and process parameters in stress corrosion of aluminum alloys generally or in malfunctioning of the LAW rocket system specifically. It does appear evident that subtle differences in processing result in subtle differences in the character of the metal in the final product, which may, in turn, have profound effects on such things as the stress corrosion characteristics. It is beyond the ability of existing material and product specifications to adequately control these subtleties. Lacking this, therefore, it is necessary that materials selected for critical applications be tolerant of the inevitable processing variability and production defects which present-day quality control measures are unable to screen out. In the case of the selection of 7001 aluminum for use in the LAW, this obviously was not done.

ACKNOWLEDGEMENTS

ARRADCOM fractographic and fracture toughness data from the early rocket motor malfunction investigation were provided by Mr. J. Rinnovatore and Mr. J. Mulherin, respectively. Dr. J. Kohatsu and Mr. C. Gazzara, both of AMMRC, performed the metallographic and X-ray residual stress analyses, respectively.