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Research paper

Root Cause Analysis for a Gas Generator and Ejection Seat System for Aircraft Applications

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Abstract: The present article focuses on the application of Root Cause Analysis (RCA) of brass cartridge cases that fail after proof trials, before batch clearance for acceptance of hardware. The empty cases for proof trials were filled with a nominal mass of explosive and were conducted at elevated (+55^{0}C) temperature. However, filled proof trials were conducted with a nominal mass of explosives conducted at (+45^{0}C) temperature. Visual examination, wall thickness measurement, chemical analysis, hardness measurement and microstructural study of the base material were undertaken. RCA plays an important role in the design and development cycle of gas generators. Gas generators are installed in aircraft seats as well as on various aircraft platforms to operate different kinds of mechanisms and systems. The novelty in this research is that it is an attempt to carry out the RCA on gas generators pertaining to aircraft applications for seat ejection. The gas generator in seat ejection systems plays a pivotal role in the safe and rapid ejection of the pilot in an emergency situation. The failure of such devices leads to consequences for the launching of various systems. This research paper focuses on the RCA of failure in gas generators for pilot seat ejection for identifying root causes, and solutions for preventive and corrective actions to avoid re-occurrence of such failures in future.

Keywords: Root Cause Analysis, gas generator, failure modes, seat ejection, pilot safety, aircraft safety, fault diagnosis, maintenance

1 Introduction

Various kinds of literature are reported for failure/defect investigation pertaining to ammunition used in defence applications. Sharma *et al.* [1] reported the failure investigation of a cartridge case. They investigated the microstructure of the cartridge cases at different locations and correlated this with hardness. Furthermore, the study revealed that the cartridge case had failed due to Stress Corrosion Cracking (SCC). Song *et al.* [2] carried out theoretical and numerical investigations on the headspace of cartridge cases considering axial deformation and movement. Fitri *et al.* [3] studied the quality analysis of defective 5.56 mm ammunition using the Taguchi method. Gamage *et al.* [4] have explained the acceptance of Taguchi's Quality Philosophy and Practice by Lean practitioners in apparel manufacturing. Mohammad and Roozbeh [5] stressed the important concepts for solving problems related to quality in research information systems by considering a case study using a thorough study. Edwin [6] has explained the investigation and root cause of rubber seal used in primary package and suggested solutions for this problem. The probable cause of failure of rubber seal is due to improper installation, wear and tear, chemical exposure, and extreme temperatures. Parate [7,8] studied the failure analysis of cartridges under different situations. Ejection seats are an integral part of a pilot's safety system, designed to ensure quick and safe ejection from an aircraft in emergency situations. The ejection seat for a pilot utilizes a gas generator to propel the seat and prepare the escape route for saving the pilot's life in an emergency. The gas generator in these aircraft seats must function with high reliability under various environmental conditions, including extreme altitudes, temperatures, and pressures etc. Failure in a gas generator can result in delay or ineffective ejection, which may lead to severe injury or fatality to the pilot. In the present research paper, a sample size of 32 cartridges, out of a total of 1000, were subjected to Closed Vessel (CV) firings at +55 °C before acceptance of the batch before filling. The sampling plan was single (Normal), inspection level was II (General), and Acceptance Quality Level (AQL) was 0.65 for major defects and 2.65 for minor defects. Cracks or burst fall under major defects. After firings of 32 samples, it was observed that four of the cases were found defective, in which one showed a burst (cracks and holes) and three indicated cracks. To investigate the cause of the cartridge case failures, visual examination, chemical analysis, hardness measurement, thickness measurement and microstructure examination were carried out on the fired brass cartridge cases. Gas generators are the heart of ejection seats used in aircraft applications. They convert chemical energy of the propellants into mechanical energy through a series of thermodynamic processes, including compression, combustion, and expansion. This energy drives the aircraft seat's propulsion system or generates electricity for auxiliary systems such as the starting of a turbine, seat ejection etc. However, failures in gas generators can result in significant operational disruption, downtime, and, in extreme cases, catastrophic failure in the case of ejection of the pilot, launching of missiles or releasing of bombs. Therefore, ensuring the reliability and performance of gas generators is crucial for maintaining aircraft safety and operational efficiency. The gas generator is a critical system in both civil and military aircraft. In civilian aviation, gas generators are typically used in turbofan and turbojet engines. In military applications, they are found in seat ejectors for fighter and trainer aircrafts, drones, and other high-performance aircraft applications. Failures in these systems can severely impact aircraft performance and safety, leading to mission delays, unplanned maintenance, and potentially crashes. Root Cause Analysis (RCA) is a structured method used to investigate and identify the underlying causes of failures or malfunctions. It is the method used to discover the root causes of problems or faults and to find the correct solutions. This process assumes that it would be much more successful to methodically avoid and address essential issues than just treating symptoms ad-hoc. It is commonly used in telecommunications, manufacturing, IT, operations and industrial process control. This approach aims to prevent the recurrence of issues by addressing the root causes rather than just the symptoms. The aviation industry, with its stringent safety regulations, has adopted RCA as a critical tool in troubleshooting, maintenance, and the continuous improvement of gas generators. The application of RCA to gas generators in aircraft applications is essential to ensure the safety, reliability, and operational readiness of an aircraft fleet. Gas generators serve as a critical component that is responsible for converting a propellant into combustible gaseous products in order to eject the pilot. Failure in a gas generator can lead to catastrophic consequences, making the identification of the root causes of failure vital. This research paper presents a systematic approach for conducting RCA on gas generators, identifies failure modes, discusses methodologies employed in RCA, and proposes recommendations to mitigate recurring issues.

2 Description of a Gas Generator

The gas generator described in this paper is filled with double base propellant i.e. nitrocellulose and nitroglycerine and a pyrotechnic composition as energetic materials. The function of the gas generator for the specific application under this study are:

– to release the lower harness,
– to fire a Barostatic Time Release Unit (BTRU) cartridge in case of failure of Cartridge Manual Separation (CMS),
– to fire the cartridge drogue secondary in the case of failure of the drogue primary.

A gas generator for aircraft application consists of the cartridge case, propellant, celluloid cup, washer and disc assembly, pyrotechnic composition (ME 424) and rubber washer. The cartridge case and washer are made of brass, the sealing washer from neoprene rubber and the disc from copper. The cartridge case is a critical component. Most of gas generators are primarily made from brass, which consists of approximately 38 wt.% zinc, 57 wt.% copper, along with trace amounts of elements such as lead (Pb), tin (Sn), iron (Fe), arsenic (As), nickel (Ni), antimony (Sb) and aluminium (Al) [8]. The initiator cap is filled with lead styphnate (32 to 44 mg) for initiating the explosive train. This is a percussion type cap and is initiated by the striker of the firing mechanism equipped within the housing of aircraft gun. The engineering sketch with labels and a photo of the cartridge components used in a gas generator are depicted at Figures 1 and 2, respectively.

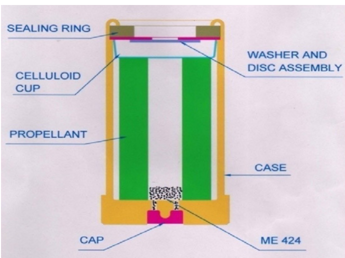


Figure 1. Engineering sketch

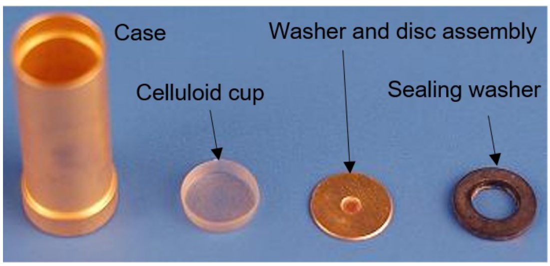


Figure 2. Cartridge components

The Material of Construction (MoC) from which the cartridge case is manufactured is brass. The case is manufactured by machining from a brass rod, followed by an annealing process to a distance of 7 mm near the mouth to achieve the desire hardness. Zinc, when properly dissolved into the alloy, enhances its properties, significantly improving its hardness and tensile strength compared to pure copper, though it slightly reduces its ductility. This study investigates the failure of a cartridge case by analyzing its microstructure at various locations and correlating these findings with hardness measurements. Failures such as longitudinal cracks and holes were observed after the conduct of firing of cartridge cases during an empty proof. Hardware without any such defects is the acceptance criterion for undertaking a production batch. The cartridges were fired in a Closed

Vessel (CV) at a temperature of 55 °C. The volume of the CV was 178 ±5 cm^3. The microstructure examination revealed a two-phase composition, alpha (α) and beta (β). Hardness higher than the specified limit is the primary cause of failure in a brass cartridge case. The mechanical properties of brass material are modulus of elasticity (100 GPa), tensile yield strength (280 MPa), tensile ultimate strength (395 MPa), hardness (90-115 HV), percentage elongation (12), coefficient of thermal expansion (1.8e-005/°C), density (8400 kg/m^3) and Poisson's ratio (0.33). Mechanical properties such as 0.2% proof stress, % elongation and tensile strength of a brass cartridge case (unfired) were established in the design phase. The heat lot at that time and the production lot are entirely different. Therefore, this is not taken into account in the present RCA as the root cause is identified and the mechanical properties of the case were ensured before commencement of cartridge manufacture, except for hardness.

3 Case Study: RCA of Gas Generator Failure in a Cartridge Case

In the present study, a real-world example of a gas generator failure was due to cracks and blow holes on the cartridge case, noticed after conduct of proof trials. The failure was traced as due to not controlling the annealing process to maintain the required hardness as per drawing and specification. This involve an in-depth investigation and a cross-functional team approach to seek long-term solutions. The following steps were used:

– **Step 1: Identify the problem:** During a routine test, visual checks on the cartridge case before installation or loading of the cartridge on the aircraft seat ejection gun **were** carried out .
– **Step 2: Data collection:** Test data, maintenance logs, storage conditions and inspection reports were reviewed.
– **Step 3: Apply RCA methodologies:** The mechanical strength relates to the thickness of the cartridge walls. The case thickness is sufficient to withstand the pressure generated inside the cartridge case. However, as the hardness of the cartridge case is more, it becomes brittle and make it more susceptible to failure under specific conditions that gets cracked due to reduced ductility. The maximum pressure generated inside the case is 35 MPa, i.e. below the tensile yield strength of 280 MPa. The failure was traced as due to the hardness being higher than the specified value as laid down in the drawings and specification.
– **Step 4: Corrective action:** Thorough 100% hardness checks on the brass cartridge case were implemented after the annealing process at the mouth of

the cartridge case. The annealing process was strictly adhered according to the procedure laid down in the specification to achieve the required hardness.

4 Results and Discussions

A systematic analysis was carried out that included visual examination, inspection of the wall thickness, chemical analysis, hardness measurement and microstructure of the base material.

4.1 Visual examination

Visual examination of fired cartridges after conduct of empty proofs was carried out as shown in Figure 4. This shows an unfired cartridge (serial number 1), and serial numbers 2, 3 and 4 show longitudinal cracks on the cartridge surface. Crack and blow holes (bursts) at the mouth and base are indicated in serial number 5. Cartridges 2, 3 and 4 show longitudinal cracks starting from the mouth and ending approximately middle distance. Cartridge 5 (burst) shows the longitudinal crack starting from the mouth and ending near the base of the cartridge case with a hole. An enlarged view of a cartridge case showing a longitudinal crack and a burst is shown in Figure 5.

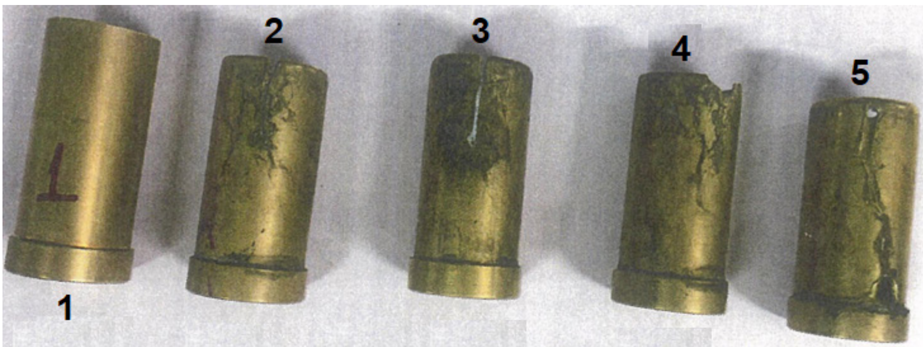


Figure 4. Visual examination of brass cartridge cases after firing

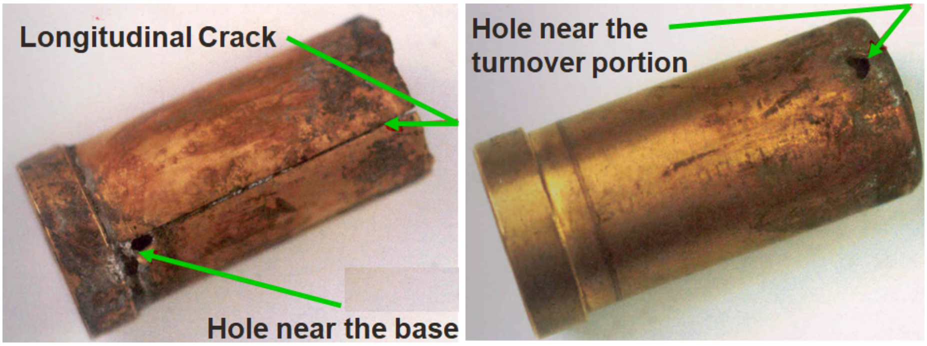


Figure 5. Enlarged view of cartridge case indicating a longitudinal crack and a burst

4.2 Measurement of wall thickness

Dimensional inspection near the fractured region of the failed cases was carried out to assess the variations in the wall thickness of the cartridges. These results are given below.

Minimum wall thickness (body) as per drawing = (minimum outside diameter – maximum internal diameter)/2 = (20.90 – 18.55)/2 = 1.175 mm

Upper and lower limit of wall thickness = 1.2 to 1.175 mm

Measured wall thickness = 1.2 to 1.24 mm

Minimum wall thickness (mm) at the mouth as per drawing = (minimum outside diameter- maximum internal diameter)/2 = (20.90-19.75)/2 = 0.55 mm

Upper and lower limit of wall thickness = 0.6 to 0.55 mm

Measured wall thickness at the mouth = 0.59 to 0.65 mm

From the above calculations, it was concluded that although this thickness is sufficient to withstand the pressure generated by the cartridge, high hardness leads to development of cracks and blow holes due to not maintaining the hardness values within specified limits.

4.3 Chemical analysis

Chemical analysis of both fired and unfired samples were determined using optical emission spectrometry. The results are listed in Table 1[9]. From these results, it was concluded that the case is made up of copper/zinc with a ratio of 57/38 and other ingredients. From Table 1, it is observed that the cartridge cases meet the chemical specification.

Table 1. Chemical analysis of both fired and unfired samples

Case	% Elements present / Chemical composition								Base
	Zn	Pb	Fe	Al	Sb	As	Sn	Ni	Cu [%]
1. Unfired	38.74	2.531	0.364	0.10	0.02	0.04	0.68	0.292	57.07
2. Fired (Crack)	39.07	2.483	0.390	0.10	0.02	0.03	0.65	0.283	56.80
3. Fired (Crack)	39.46	2.422	0.412	0.10	0.02	0.03	0.67	0.282	56.42
4. Fired (Crack)	38.59	2.462	0386	0.10	0.02	0.03	0.66	0.285	57.30
5. Burst	38.68	2.501	0.387	0.09	0.03	0.04	0.66	0.282	57.23
Specified brass to IS:319, Grade-1	Remainder	2 to 3.5	0.35 max	Total impurities except iron 0.7 max					56 to 59

4.4 Hardness measurement

Hardness tests at the base, middle and mouth of cases of fired and unfired brass cartridge samples were measured using a Digital Vickers Hardness tester at 5 kg load. A Leco (make) equipment LV 700 L (model) was used for the hardness measurements. The results are listed in Table 2. From these results it was observed that hardness at the base and middle of the cartridge case is close to upper limit. The hardness near the mouth was greater than the upper limit, making the material brittle in nature. This brittleness leads to propagation of cracks and blow holes.

Table 2. Hardness test of both fired and unfired brass cartridge samples

Case	Hardness in HV at 5 kg load		
	Base	Middle	Mouth (up to 10 mm after annealing
Specified range IS 319 Grade 1 HB Condition	120-150	120-150	90-110 as per drawing
1. Unfired	141-145	141-143	115-123
2. Fired (crack)	145-148	143-145	130-137
3. Fired (crack)	140-143	135-142	132-139
4. Fired (crack)	145-150	135-144	128-136
5. Burst (crack and hole)	145-150	144-146	139-144

From Table 2, the higher hardness of the case for unfired and fire cases were of almost in the same range. This leads to crack initiation of the cartridge case. Finer grains in the brass microstructure lead to higher hardness. Smaller grains provide more grain boundaries, which act as barriers to dislocation movement, thereby increasing hardness. Cold working (*e.g.* rolling or drawing) processes refine grains and increase dislocation density, enhancing hardness. As the hardness is more than the specified values, the mode of failure is due to brittle failure. Brittle failure is sudden failure without giving any warning.

4.5 Micro-examination

For micro-examination, samples in longitudinal and transverse directions were cut and prepared using standard metallographic techniques. For comparison purposes, samples from unfired cases were also prepared for micro-examination. In the un-etched condition, elongated lead stringers were observed as shown in Figures 6(b) and 6(d). These are for cartridge case number 1 image in Figure 4 for an unfired cartridge [10]. When the prepared samples were etched with potassium dichromate solution, microstructure at the base, middle, and mouth of the cartridge case revealed the presence of two-phase (alpha and beta phases) with dispersion of lead globules and lead stringers throughout the matrix. The lead globules is depicted in Figure 6(a) and, lead stringers and black particles in Figure 6(b) at 100 X. The lead globules is depicted in Figure 6(c) and, lead stringers and black particles in Figure 6(d) at 200 X. Figure 7 indicate the cartridge case of two two-phase with slightly coarser and elongated alpha grains in the matrix of beta and black lead stringers. Figure 8 depicts shows a case with cracks and blow holes at the mouth and base. This is for the cartridge serial number 5 as shown in Figure 4, a fired cartridge with cracks and blow holes at the mouth and base after firing. A total of four defects were observed for the cartridge cases after conducting of empty proofs trials at 55 °C.

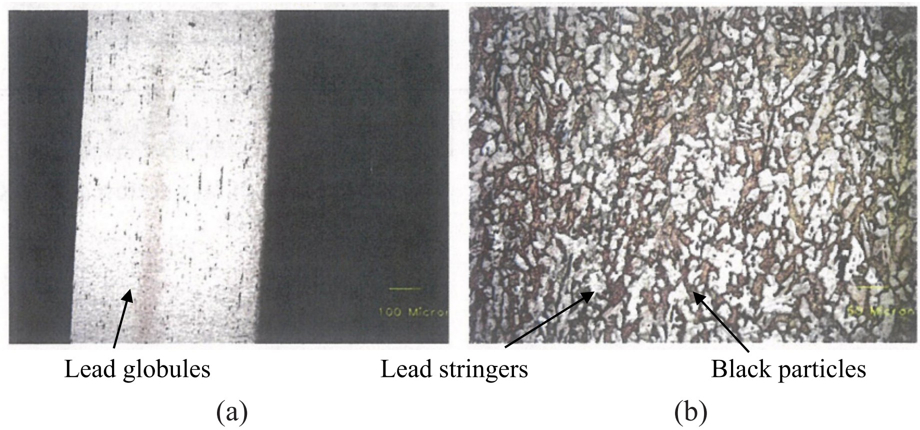


Figure 6. Micro-structure of an unfired brass cartridge case indicating two-phase structure (α and β phases) and black particles and stringers of lead at 100 X

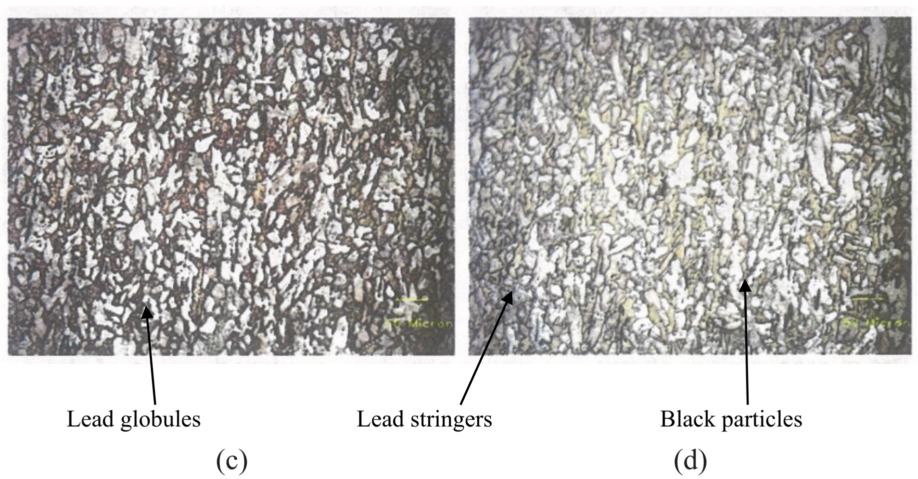


Figure 6. Micro-structure of an unfired brass cartridge case indicating two-phase structure (α and β phases) and black particles and stringers of lead at 200X

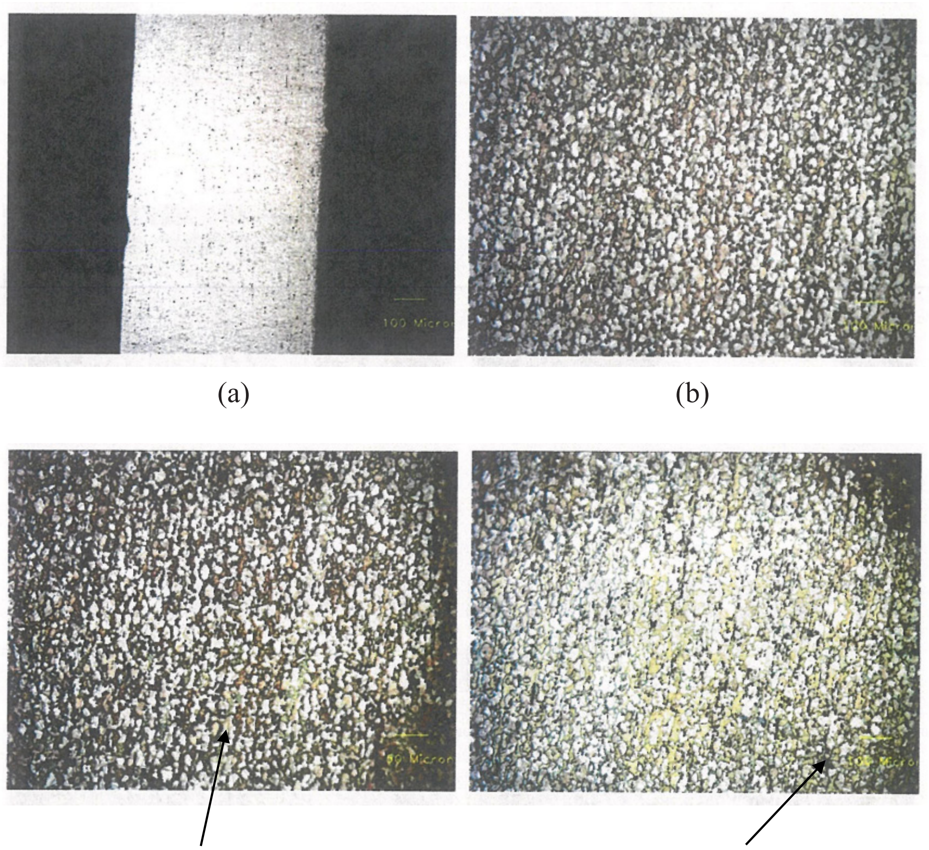
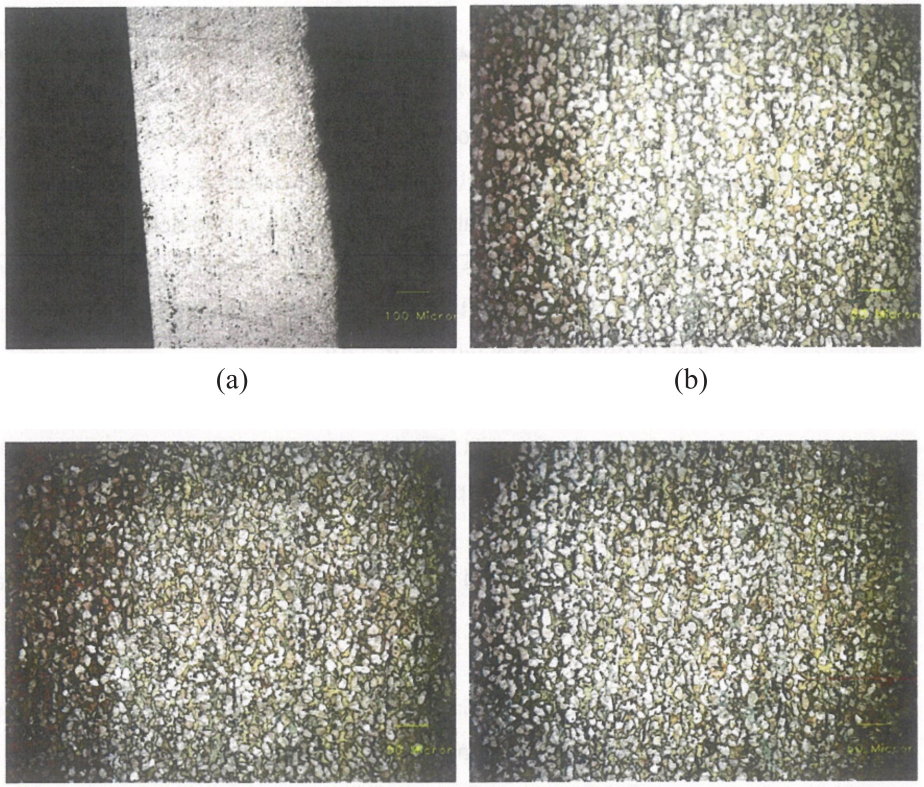


Figure 7. Micro-structure, at 200X, of a fired brass cartridge case indicating two-phase structure, slightly coarser and elongated α grains in the matrix of β and black lead stringers in longitudinal section: – unetched (a), and etched: – base (b), – middle (c) and – mouth (d)



(a) (b) (c) (d)

Figure 8. Burst brass cartridge case (crack and holes at mouth and base), at 200X, two-phase structure α and β, equixed α grains and black lead particles (in longitudinal section): unetched (a), and etched: – base (b), – middle (c) and – mouth (d)

Micro-examination of un-etched fired and failed cartridge cases clearly shows that the two-phase structures (α and β) is as normally shown in free cutting brass. Cartridge cases numbers 2, 4 and 5 show fine equiaxed alpha grains which are not observed in cartridge case numbers 1 and 3. Alloys with a dual-phase ($\alpha + \beta$) microstructure are generally harder than single-phase α brass due to the harder β-phase.

5 Conclusions

By applying RCA, it is possible to identify the underlying causes of gas generator failures and to improve safety measures, reducing the risk of catastrophic failure during ejection. RCA is a systematic approach used to identify the underlying causes of failures or malfunctions in complex systems. RCA, when applied to gas generators in ejection seats, helps to identify failures that compromise the pilot safety.

- The following are recommendations to avoid a recurrence of defects such as longitudinal cracks, blow holes (bursts) in future:
  - Hardness of the cartridge case to be maintained as per the drawing.
  - The annealing process is to be strictly followed to achieve the desire hardness.
- Root Cause Analysis (RCA) is a crucial tool in maintaining the safety, reliability, and performance of gas generators in aircraft applications. By systematically investigating failures and addressing their underlying causes, RCA helps to prevent recurring problems and ensures continuous operational efficiency. Regular application of RCA methodologies in the design, maintenance, and operation of gas generators can improve overall system reliability and contribute to safer and more efficient aviation practices.
- RCA is an essential tool for identifying the underlying causes of gas generator failures in ejection seat systems. Understanding the common failure modes, such as propellant degradation, ignition system malfunctions, and mechanical failures, enables the development of more robust systems. The root cause has been identified and as per recommendation the same was implemented for all future production lots. The purpose of this paper was to explore the key failure modes of gas generators in aircraft applications, analyze their root causes, and discuss the RCA methodologies that can be applied to ensure more reliable and efficient operations. Cracks observed on cartridge case are unacceptable and lead to danger for safety of the pilot during ejection.
- The hardness of brass increases with finer grain size, the presence of harder phases (like β-phase), higher zinc content (within limits), and cold working, all of which influence the microstructure by impeding dislocation motion that is a key mechanism of plastic deformation.

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Contribution

Parate B.A.: conception, foundations, methods, performing the experimental part, other contributions to the publication

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