Failure Analysis of Follower Assembly in the 155mm Artillery Gun

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Abstract: The follower assembly is a critical component of the 155mm artillery gun, which acts as a safety lock for the trigger mechanism during firing and releases it effortlessly for recoiling. During the firepower mission, issues arose where the follower assembly part would constantly bend or become crooked. This resulted in the roller detaching itself from the assembly and, therefore, reducing the equipment's effectiveness and negatively disrupting the firepower mission. This failure could have major repercussions for both military operations and national defence capabilities. This study investigates the failures and subjects them to macroscopic inspection, metallographic examination, hardness testing, and fractography analysis. A close look at the microstructure showed the existence of three separate layers: an ultra-fine martensitic layer near the surface, a fine martensitic layer closer to the core, and a normal martensite layer covering the rest of the microstructure. The hardness profile also decreases from the near surface to the core of the follower (part of the follower assembly). An analysis using fractography showed small round or long dimples on the fracture surface. The analysis proved that the follower had an overload ductile fracture. The material of the follower is unknown, and a chemical composition analysis was conducted for re-engineering purposes, showing that its composition closely matches that of AISI 4340. The analysis concludes that the follower is a post-treated ductile material. The authors recommend optimising the heat treatment process to enhance its strength and toughness, along with several suggestions for future studies.

Keywords: Failure analysis, artillery gun, material testing and evaluation, fractography.

1. INTRODUCTION

Depending on their artillery systems or projectiles, such as mortars, cannons, volley rocket weapons (VFRW), and self-propelled artillery sets (SPAS), 115mm shell artillery guns can defend and destroy targets typically at a range of 24 km without range enhancement devices and can be enhanced by around 105% with ramjet technology (Becker *et al.*, 2021; Velari & Ramakrishna, 2023). Artillery guns are essential assets for any country, serving as a deterrent against potential threats, enhancing combat effectiveness in both offensive and defensive operations (Koltsov *et al.*, 2025), and providing cost-effective firepower solutions compared to expensive advanced missile systems (Huseynov, 2025; Maksymova *et al.*, 2023). Any failure or malfunction of the artillery guns during military operations can have serious implications for both operational and national defence capabilities. Therefore, regular maintenance, rigorous quality control, timely defect detection, and countermeasures are essential to mitigate risks and ensure the artillery guns remain operational and reliable (Peruvian, 2024). The investigation by the firepower mission team has identified the 155mm artillery gun's follower assembly failure as the cause of the problem. Failure analysis on the follower assembly samples was done through various processes, including background information collection, visual and macroscopic inspections, sample testing, and evaluations, as recommended by a few researchers (Becker *et al.*, 2021; Donald J. Wulpi, 2013; Sivaraman & Singh, 2022; Viana, 2025). Additionally, the chemical composition analysis was conducted to identify the unknown follower assembly material.

Not much failure analysis research has been openly published on military artillery gun components. Most studies focus on the barrel components and scarcely on the recoil components, such as the follower assembly. This study was one of the earliest joint investigations conducted by the Malaysian Royal Artillery Regiment (*Rejimen Artileri DiRaja Malaysia*) and the Science & Technology Research Institute for Defence (STRIDE). It has provided several guidelines for establishing standard operating procedures (SOPs) for investigating military component failures, contributed expert data to the material system portal (MATSYS), improved the artillery follower assembly and firing activities, and reduced costs for military operations and component purchases. This paper concludes with brief recommendations for the future study.

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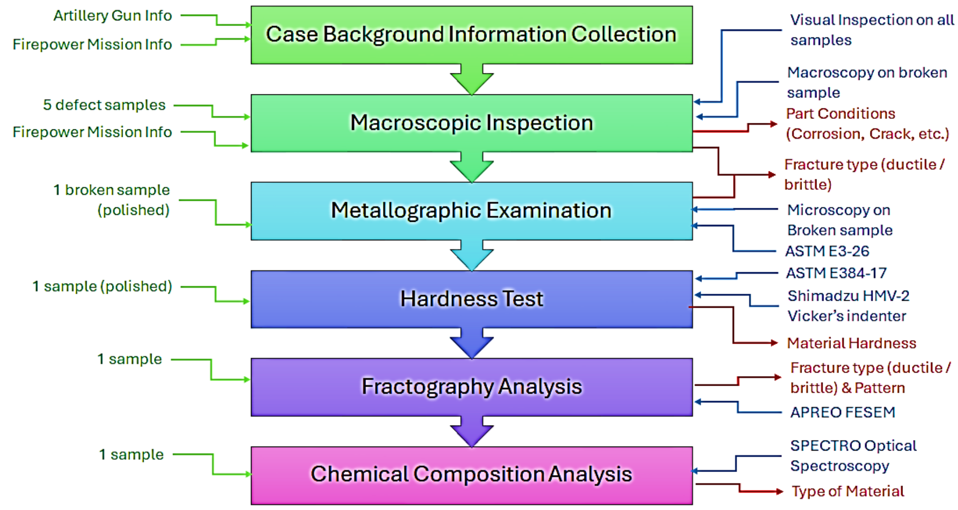

Figure 1: A brief process flow of the failure analysis methodology (incl. requirements and outcomes).

2. FAILURE ANALYSIS METHODOLOGY

Failure analysis is a systematic process that involves investigating, identifying, and understanding the causes of failures in materials, components, systems, or processes. It employs multidisciplinary approaches to prevent the recurrence of similar failures by optimising design, manufacture, or maintenance practices (Becker *et al.*, 2021; Sivaraman & Singh, 2022; Viana, 2025). Industries such as aerospace, manufacturing, civil engineering, electronics, and automotive commonly use failure analysis, and generally, most researchers agree that items in failure analysis methodology are typically (Donald J. Wulpi, 2013; Sivaraman & Singh, 2022; Viana, 2025): problem definition; obtaining background information; investigating evidence (macroscopic and microscopic examination, including SEM); evaluating failure mechanism sequences and causes; performing exemplar tests, analysis and calculations, FEM and fracture mechanics analyses, and risk assessment; drawing conclusions based on all evidence; and making recommendations.

This study conducted a failure analysis on five defect samples of the follower assembly. Reports indicate that after 10-15 firings, the follower assembly consistently bends or becomes crooked, leading to the roller detaching from the assembly and disrupting firepower operations. To identify the root causes, the defect samples were analysed by using the following failure analysis process flow (Figure **1**): The process included the collection of case background information, such as macroscopic inspection, metallographic examination, hardness test, chemical composition analysis, and fractography analysis. Figure **1** also provides a brief overview of the requirements and outcomes of the analysis.

3. FAILURE ANALYSIS AND RESULTS

3.1. Artillery Gun and Firepower Mission Information

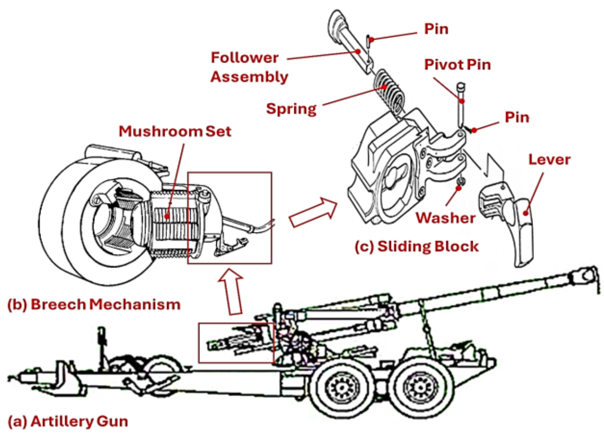

Figure 2: Artillery gun (a) main structure, (b) breech mechanism and sliding block sub-assemblies, and (c) its components (including follower assembly).

The follower assembly is a key component of the breech block in the artillery gun, responsible for ensuring safe and efficient projectile or ammunition loading, firing, and unloading operations (Figure **3**). The follower assembly ensures correct alignment, prevents the breech mechanism from wearing down for smooth opening and closing, disperses firing forces to prevent damage to the breech

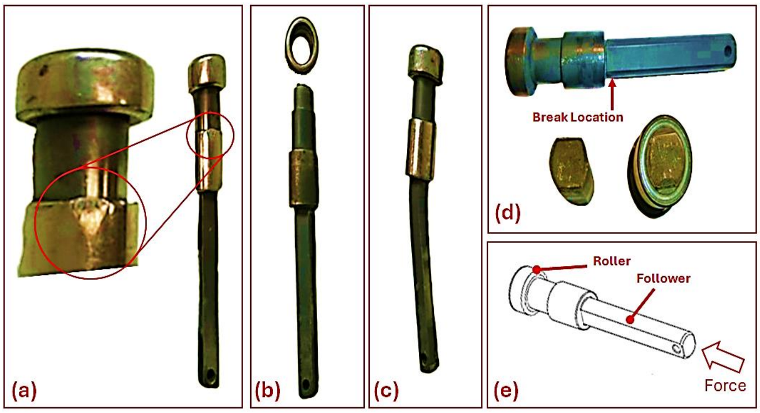

Figure 3. Types of failure: (a) dented body, (b) dislodged roller, (c) bent, and (d), broken followers; and (e) the force direction acted on the follower assembly.

mechanism, and safeguards the gun chamber by preventing gas leaks and backblasts during firing. In essence, the follower assembly locks the trigger mechanism during firing and then unlocks it after firing, thereby readying the gun for the next firing and supporting the recoil system.

Gunners followed the manufacturer's recommended time intervals for firing rates during firepower practice to ensure the artillery gun's reliability and effectiveness. Depending on the combat scenarios, the firing rates range from a slow rate of 1 shot every 3 min to a maximum rate of 3 shots per min. Immediately after firing, the gun barrel's measured pressure can reach up to 420 MPa and 1,200K, and it cools down within a few seconds (Dubey & Sharma, 2022).

3.2. Macroscopic Inspection

Macroscopic inspection was conducted to briefly evaluate the presence of any defects, such as corrosion, misalignment, cracks, and physical damage. Generally, the follower assembly has two components: the follower and roller (Figure **3**(e)). A visual inspection categorises the samples into four types of failure, as illustrated in Figure **3** (a) dented body, (b) dislodged roller, (c) bent follower (two samples), and (d) broken follower. All these failures result in disruptions in firepower missions.

Figure **3** (e) identifies the firing force's direction as straight along the follower assembly. All samples were observed to exhibit impact, bent, or broken marks approximately at the same location (Figure **3** (d)). Further investigation indicated that the force at this location was most probably due to the recoiling force (Ibrahim Doruk *et al.*, 2010; Li *et al.*, 2021).

Further inspection with lower magnification was performed to detect defects, such as cracks, porosity, surface irregularities, or inclusions, that are not easily visible with the naked eye. Examining the broken (fracture) sample revealed two rupture regions, indicated by a flat surface with minimal deformation and sheared marks (Figure **4**). Regions A and B are the initial and final fracture regions, respectively.

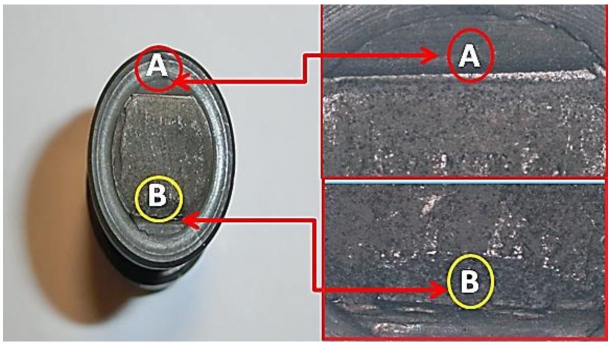

Figure 4: Macroscopic image of the broken follower with fracture regions A (initiation) and B (final).

This finding concluded that the specimen is a relatively tough material, having undergone extreme force prior to fracture. The crack propagation was not clearly visible at the macroscopic level, suggesting that the sample might possess exceptional mechanical properties through comprehensive material improvement, alloying addition, mechanical working, or microstructure manipulation (William D & David G Rethwisch, 2020). The material may exhibit ductility in the sample due to its ability to bend prior to fracture, as evidenced by the availability of a bent sample, and the absence of macroscopical brittleness. The next investigations provide further confirmation.

3.3. Metallographic Examination

Metallographic examination was conducted using high-magnification microscopes to investigate the inner structure of the follower. The specimen preparation is as per recommended in (ASTM Standard E3-26, 2026). A defect sample was cross-sectioned, and the portion was mounted with Bakelite powder by using a LEICO hot press mounting for curing. The sample was ground using silicon carbide paper with grit sizes of 240, 400, 800, and 1,000 to minimise surface scratches. The ground sample was then polished using an appropriate non-metal polishing cloth together with a diamond paste (grit size of 6μm to 1μm) to form a mirror-like surface. After cleaning, drying, polishing, and etching with 2% Nital reagent for about 5 s, the microstructure for examination was revealed.

The test (Figure **5**) showed three different layers of phases in the microstructure: ultra-fine martensitic (near the surface), fine martensitic (towards the core), and normal martensite (the rest of the microstructure of the material). These changes occur due to the alteration of the ultra-fine martensitic composition in the layers during material treatments. The surface cools down faster than the core, creating a higher martensitic transformation on the surface and a softer ferrite or pearlite microstructure in the core (Karroum *et al.*, 2024). This confirms that the follower underwent quenching and tempering processes, including heat treatment, after the machining process.

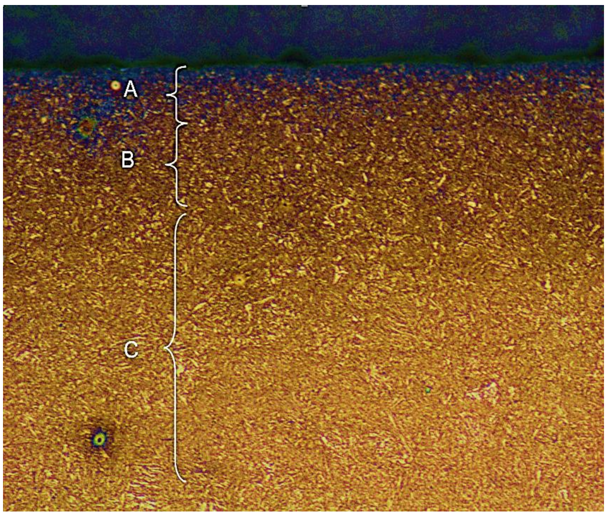

Figure 5: Metallographic examination (at 200x magnification) revealed (A) ultra-fine martensitic, (B) fine martensitic, and (C) normal martensitic regions. Region (A) is near the surface.

3.4. Hardness Test

To ensure that the mechanical properties of the investigated sample meet specific performance requirements, such as its resistance to deformation, scratching, and penetration, hardness test was performed on the sample, according to the (ASTM Standard E384-17, 2022). A cross-sectioned sample was polished to a mirror-like finish and then a load of 9.807N (HV1) to the Shimadzu HMV-2 Vickers indenter for 10 s. The hardness values of the sample were then measured starting from approximately 10μm near the surface or edge (No. 1) towards the core or middle section (No. 10) with the distance between each indentation point of at least three times the indentation diameter.

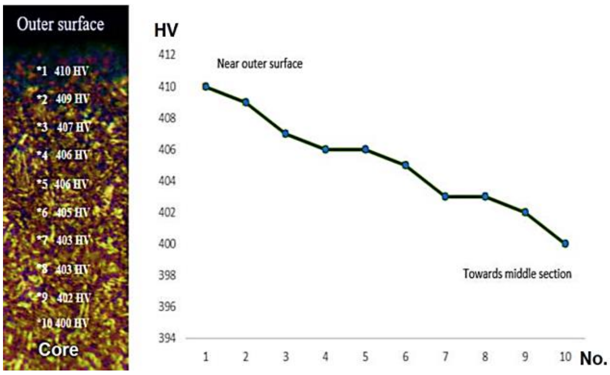

Figure 6: The result of the hardness test (Vickers) on a cross-sectioned sample, tested from the near surface to the core with the ASTM E384-17 standard.

The test result presented in Figure **6** showed that the hardness reduces from outer to inner layers. Variations in the ultra-fine martensitic composition between the layers following heat treatments could potentially explain this. The previous metallographic examination concluded a similar finding (Sultan *et al.*, 2024).

3.5. Fractography Analysis

The fractographic analysis provides insights into material failure mechanisms (ductile, brittle, or mixed-mode) and microstructural behaviour under different loadings (fatigue and overloading) and environmental conditions by examining the entire fracture surface, including crack features, such as dimples, hallmarks, microvoids, cleavage facets, river patterns, intergranular fractures, and striations at both macroscopic and microscopic levels (Becker *et al.*, 2021; Schroeder *et al.*, 2024).

Figure **7** and Figure **8** show fractography of crack feature examples and crack features of

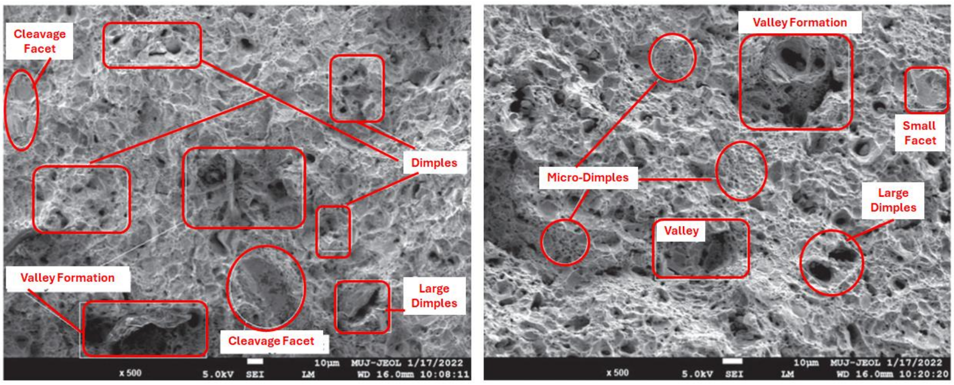

Figure 7: Examples of fractography crack features (Dewangan *et al.*, 2022).

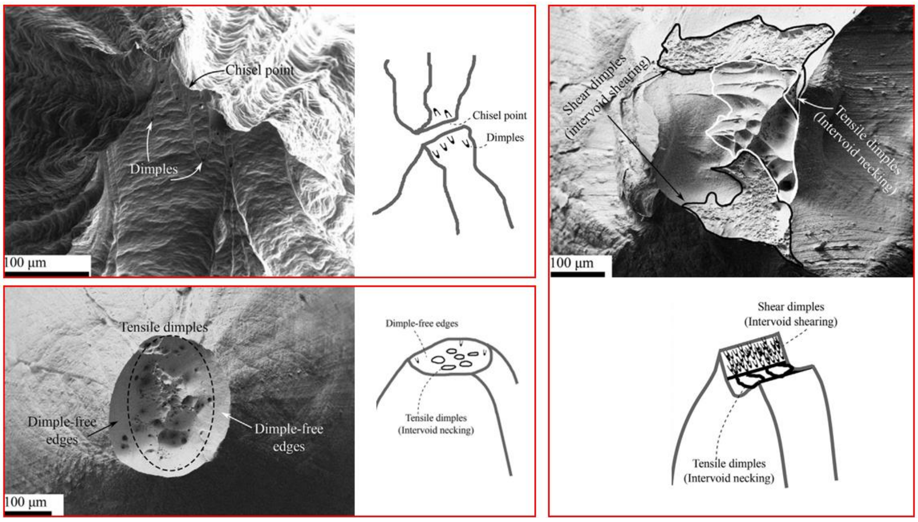

Figure 8: Examples of fractography of ductile fracture with difference rupture mechanism (Noell *et al.*, 2018).

different ductile rupture mechanisms (Dewangan *et al.*, 2022) and (Noell *et al.*, 2018), respectively.

The scientific APREO field emission scanning electron microscope (FESEM) was utilised for this analysis, capturing images of the fracture surface on the broken sample in three regions, as shown in Figure **9**. The fractography revealed that the material underwent overload ductile fracture, with dimples dominating the microstructure, as predicted by the previous macroscopic inspection. The varying dimple sizes indicate the ductility and toughness of the material, where larger dimples mean low stress concentration (high energy absorption during failure) and extensive plastic deformation and, therefore, high ductility and low toughness (low hardness). The images showed an increase in dimple size from the initiation (Figure **9** (a)) to the final (Figure **9** (c)) rupture regions, which suggests a reduction in toughness as the material transitions from constrained to less constrained stress states due to plastic deformation differences in those regions. Additionally, numerous small, round, or elongated dimples indicated that the sample experienced overload prior to fracture, similar to previous claims in macroscopic inspection

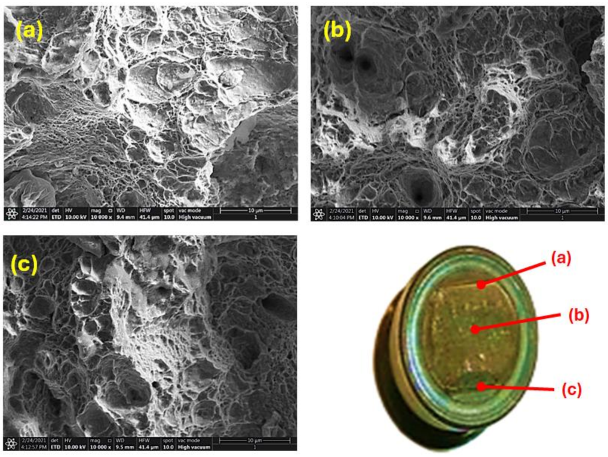

Figure 9: Fractography of follower with 10,000x magnification at the fracture regions: (a) initiation, (b) middle, and (c) final.

3.6. Chemical Composition Analysis

Chemical composition analysis was performed to determine the material of the unknown follower, which the manufacturer did not specify. These data would be useful for re-engineering and manufacturing the follower. A sample was analysed by using SPECTRO optical emission spectroscopy equipment, and the results are given in Table **1**.

Table 1: The chemical composition of the follower and compared to (Tikhe *et al.*, 2023).

Element	Chemical Composition (wt%)	
	This study	(Tikhe *et al.*, 2023)
Iron (Fe)	94.6	95.843
Carbon (C)	0.298	0.39
Nickel (Ni)	4.22	1.69
Chromium (Cr)	1.18	0.81
Manganese (Mn)	0.590	0.77
Silicon (Si)	0.263	0.25
Mo	0.0443	0.23
P	0.0005	0.017

Based on this result, the sample has a close match to the AISI 4340, which possesses exceptional properties: strength, ductility, hardness, and toughness (Tikhe *et al.*, 2023). These properties made the material suitable for various critical sectors, such as military, nuclear power plants, and aircraft components (Ali *et al.*, 2026).

Based on this finding, the authors recommend enhancing the heat treatment process of the follower to boost the material's strength and toughness by manipulating the quenching and tempering parameters, such as cooling medium, temperature, and time (Sultan *et al.*, 2024; Tikhe *et al.*, 2023).

4. SUMMARY, CONCLUSIONS AND FUTURE RECOMMENDATIONS

The investigation by the firepower mission team has identified follower assembly failures after 10 to 15 firings as the main cause of firepower mission interruptions. Case background information was collected to understand the functioning of the follower assembly in the artillery gun and the execution of the firepower mission. Failure analysis is done on 5 defective samples of the follower assembly (1 dented, 2 dislodged rollers, 1 bent, and 1 broken) to determine why they failed. This is done using different techniques, such as macroscopic inspection, metallographic examination, hardness testing, chemical composition analysis, and fractography analysis.

Upon macroscopic inspection, it was found that all samples exhibit impact, bent, or broken marks nearly at the same location, likely due to the action of the recoiling force. On the broken sample, initial and final fracture regions with a flat surface (minimal deformation and sheared mark) were observed, indicating the sample's toughness and the tremendous force it endured before fracture. The non-visibility of crack propagation on the broken sample indicates that the sample has excellent mechanical properties due to alloying addition, mechanical working, or microstructure manipulation.

Due to the limited visibility with macroscopic inspection, further intensive inspections were conducted to confirm the initial assumptions with metallographic analysis, hardness tests and fractography analysis. Metallographic analysis showed that there were three layers of martensite, ranging from ultra (near the surface) to normal (towards the middle). This was probably the sample that had been quenched and tempered after being treated with heat or other methods. The hardness test confirmed this finding, showing a reduction in hardness from the sample's surface to its core.

The fractography analysis revealed that the microstructure predominantly consisted of small round or long dimples, indicating that the sample was experiencing an overload ductile fracture process. The obtained crack propagation shows an increase in dimple size from the initiation to the final rupture regions, with the initial region being tougher than the final region. Therefore, this analysis confirms and advocates the previous findings. The follower has remarkable ductility and toughness and is heat-treated to harden and strengthen it.

As no prior material data was available for this follower, chemical composition analysis was conducted to reproduce the follower assembly, and the result indicated that the follower closely matches AISI 4340, a material known for its high strength, ductility, hardness, and toughness, making it ideal for critical applications across various sectors. As for the re-engineered follower made of AISI 4340, the authors recommended enhancing the heat treatment process to optimise its strength and toughness.

Further investigation is recommended to confirm some of the initial findings in this failure analysis. The recommended future studies are as follows:

- Improvement of firepower mission data collection by adding more sensors for force and pressure sensing acting on the breech mechanism, particularly the follower assembly.
- Conduct FEM analysis to simulate and compare the investigation, aiming for better predictions and design improvements.
- Optimise the re-engineered AISI 4340 follower with recommended post-treatment processes, such as advanced quenching and partitioning (QP) and quenching and tempering (QT) heat treatments.
- Field and mechanical testing of re-engineered follower.
- Application of advanced vision technology and machine learning to augment the failure analysis with visual inspections (from macro- to fractography).

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR'S CONTRIBUTION

Jaronie M. Jani: supervision, conceptualisation, methodology, review and editing; Amran M. Nayan: original draft extracted from his PhD thesis; M.R. Idris: supervision, methodology, and review; S.R.S. Bakar and M.Y. Ahmad: technical and facility support for specimens' examinations.

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