Failure Analysis of Stainless-Steel Rifle Barrel

416R Material Case Study

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Abstract

This document covers the investigation of a failed muzzleloader and the mechanisms behind its failure. The failure was concluded to be the cause of multiple issues, both design and manufacturing related, combined. The evidence was provided through SEM, chemical analysis, photography, and statements collected during the investigation. This report further discusses the harm, both human and financial, caused by the failure of this rifle and suggests some solutions to prevent this failure from happening in the future.

Introduction

A muzzleloading rifle, or "muzzleloaders" are firearms where a shooter or an operator is required to load a projectile and usually a powder charge(propellants) by pushing them directly into the muzzle [7]. The muzzle is the forward open end of the barrel. This is what makes a muzzleloader different from other modern firearms. Modern firearms are loaded from the rear or the breach. Muzzleloaders are also referred to as "blackpowder rifles" because they typically use blackpowder as compared to modern firearms that use smokeless powder [7].

Blackpowder is an old propellant and is considered as a "fast burning" powder [8]. Upon firing a muzzleloader, a large cloud of smoke is produced which can often block the user's vision. Additionally, because of the excess soot buildup, frequent cleaning and maintenance is required [8]. Smokeless powder, on the other hand, increases the range and power of a weapon because it produces more velocity. It is also cleaner and reduces the time necessary for maintenance of the weapon [9]. Hence, it is concluded that smokeless powder can solve the various problems caused using blackpowder. Despite the advantages, smokeless powder can potentially cause problems as well. Smokeless powder burns at a higher pressure, so the design of the barrel needs to be able to withstand high amounts of pressure [9]. Furthermore, there is more gas build-up, while using smokeless powder, which causes higher energy, which can potentially cause a large explosion.

For this failure analysis report, the rifle in question was designed and marketed as the only smokeless muzzleloader available in the market. The smokeless powder used from a company named Vihtavouri N110. Vihtavouri is a company known for "producing high quality propellants with reliable ballistic performance, long shelf-life and wide variety selection" [6].

The user of the rifle was severely injured because the barrel on the firearm split during firing (Figure 1). The rifle was said to have a 416R steel barrel. Upon questioning, it was found that the rifle was "fairly new" and had only been used 20-30 times prior to the failure. Additionally, before leaving the manufacturing facility, the rifle was proof tested with a double load of the powder.

Figure 1: Barrel split during the accident on the failed rifle

In terms of failure of the rifle, multiple issues can be linked to have been the cause. The causes include the following: Incorrect chemistry, incorrectly manufactured hole in barrel for sight mounting, and the anisotropic behaviour of the sample causing unevenly distributed properties throughout the sample.

Chemical analysis

In the muzzleloader, the barrel is usually made of stainless steel because stainless steel has two main advantages over carbon steel: high corrosion resistance and high toughness. High corrosion resistance is attributed to the chromium, which reacts with oxygen to form a layer of chromium oxide on the surface of the stainless steel. This layer works as a barrier between the oxygen and the iron, in turn avoiding corrosion. Nickel is added to increase the toughness, ductility, and strength of stainless steel [1].

The 416R stainless steel is most commonly used in the barrel because of the high machining properties. It requires heat treatment to reach high mechanical properties such as hardness and toughness. The 416R stainless steel is considered as "martensitic" steel. This martensitic steel is achieved through two heat treatment processes: quenching and tempering. Mostly, a large section of the material is quenched in oil, and a small section can be quenched in air. Because of the involved heat treatment processes and the high toughness and hardness, 416R stainless steel is difficult to be machined. The machining property is critically important for the barrel because it is required to be shaped and formed in a specific design that increases the accuracy of the barrel. The main element that is used to improve the machining for 416R stainless steel is sulfur. The sulfur particles increase the machining by creating voids in the structure of the steel. However, the sulfur reacts with iron forming iron sulfide (FeS). This phase has a low melting point and contains many ruptures [2]. To avoid the FeS phase, manganese is added to react with the sulfur to form manganese sulfide (MnS) that has a higher melting point than iron sulfide.

Typical Chemistry

Carbon	0.12%
Chromium	12.50%
Manganese	0.40%
Phosphorus	0.03%
Sulfur	0.13%
Silicon	0.40%
Molybdenum	0.40%

(a)

Work Requested: Chemical Analysis of Sample

SCRS ID 1 **Customer ID:** Steel Piece

Chemical Analysis Results

Element	1 (%)
C	0.12
S	0.17
P	0.008
Mn	0.34
Cr	12.3
Mo	0.30
Si	0.36

(b)

Figure 2: Comparison of (a) Typical chemistry of 416R Stainless Steel [10] to the (b) chemical analysis testing of the 416R stainless steel part from the barrel of the rifle Notice the highlighted (a) blue and (b) red boxes. They show the difference in Sulfur(S) percentage

The maximum concentration of sulfur in 416R stainless steel is given as 0.13% (Figure 2, (a)). In this muzzleloader's case, the chemical analysis of the barrel showed that the concentration of sulfur in the sample was 0.17% (Figure 2, (b)). Hence, there is a 0.04% difference between 416R stainless steel used in the rifle in question and the 416R stainless steel in the market.

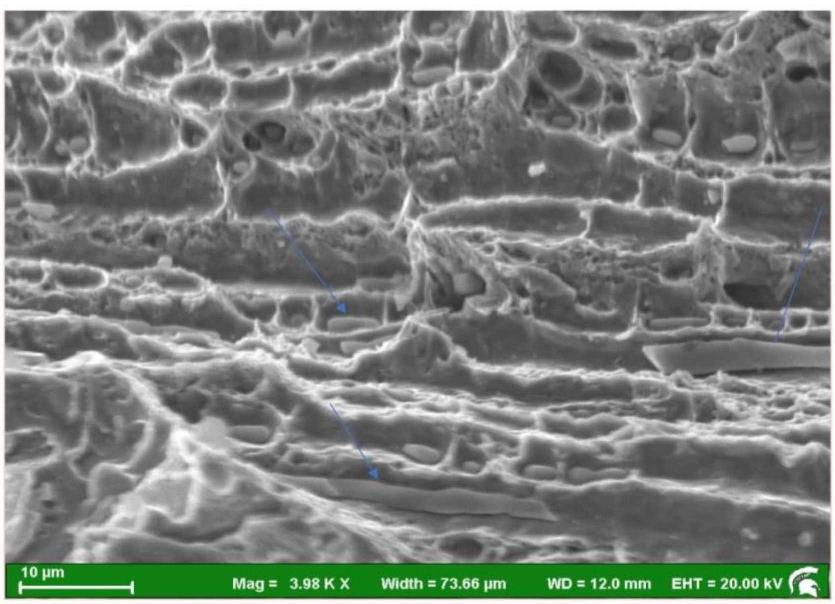

Figure 3: SEM image that shows the segregation of the MnS particles from the stainless-steel matrix. The arrows point to the MnS particles.

Because of the high concentration of sulfur, the barrel contained a high amount of MnS particles. The MnS inclusions were segregated from the steel matrix (Figure 3). These inclusions increase the softness of the steel, which, ultimately, results in easy breakage of the part. Moreover, the sulfide particles cause 416R stainless steel to be anisotropic (Figures 4 & 5). The difference in the concentration of sulfide particles in the right side of the barrel versus the left side of the barrel further confirms the anisotropicity(Figures 4 & 5).

Figure 4: Optical micrograph of the right side of the barrel. The black “stretched out lines” or “strings” represent the MnS elongation in the direction of the stress. (50x magnification)

Figure 5: Optical micrograph of the right side of the barrel. The black “stretched out lines” or “strings” represent the MnS elongation in the direction of the stress. (50x magnification)

Mounting Hole

One reason that the rifle is believed to have failed is the improperly sized threaded hole in the barrel. While the presence of a threaded hole on rifle barrels for the purpose of mounting attachments is common, the depth of the hole in question is detrimental to the rifle's safety. The design specification for this particular hole called for a maximum depth of.161in, and measurements have shown this hole to have an actual depth of .168in, which is .007in deeper than should be allowable per the specifications. This increased depth lowers the toughness of the area and creates an area of increased stress.

Furthermore, the hole extends past the threaded portion, increasing the depth of the hole significantly (Figure 6). While the threaded portion of the hole is used for mounting sights and various accessories, the unthreaded portion seemingly serves no purpose. With that being said, the unthreaded portion of the hole could easily be removed, which would greatly reduce the depth of the hole and increase the safety of the rifle without sacrificing any functionality.

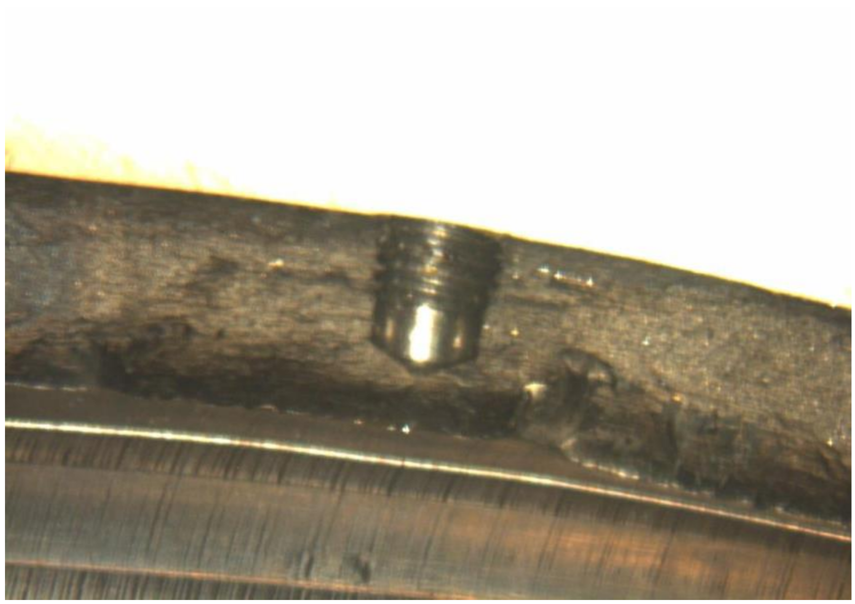

Figure 6: The hole, as seen here, extends past the threaded portion. In doing so, the depth of the hole is increased significantly.

When considering the stress state of the barrel during firing, the internal ballistics of the firing operation must be looked at. When firing the weapon, the pull of the trigger sets forth a series of events in which a primer lights the propellant, forcing the projectile forward with great velocity. The lighting of the propellant, smokeless gunpowder in this case, causes a great deal of pressure buildup within the barrel, however. In fact, the velocity of the projectile and the pressure in the barrel are directly correlated in such a way that a 3% increase in velocity requires a 6% increase in internal pressure [11]. This is important to keep in mind, as not only is this barrel already compromised by an increase in stress due to the excess depth of the mounting hole, it is also firing smokeless powder which uses an increase of internal pressure to achieve a higher velocity. With this being said, it is easy to see how the increased state of stress caused by the excessive depth of the mounting hole can combine with the high internal pressure produced from the reaction of the smokeless powder to contribute to the failure.

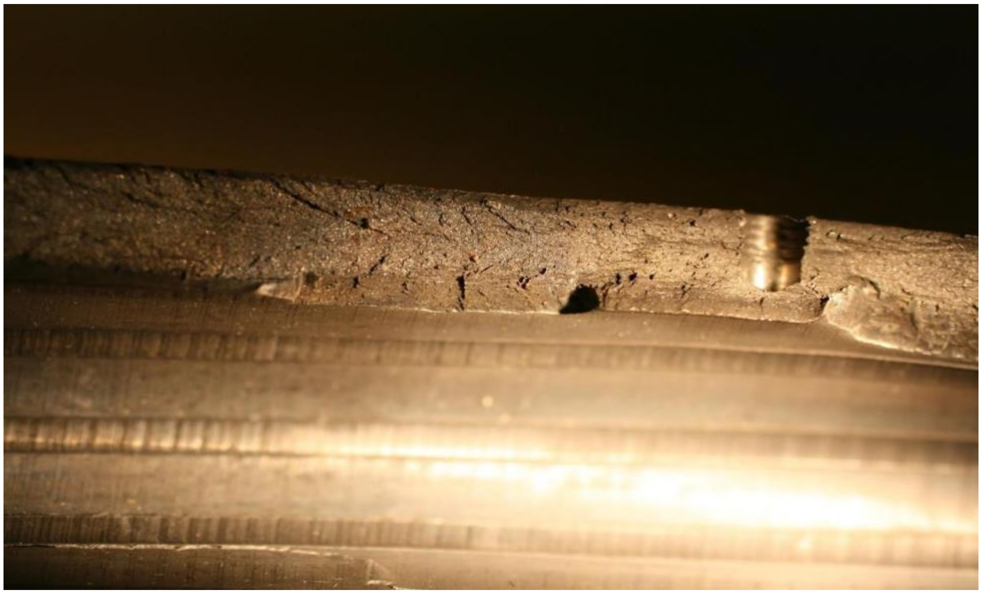

Figure 7: Chevron markings can be seen here as they point towards the origin of the fracture i.e. the mounting hole.

The chevron marks running from the hole further reinforce the idea of the hole being a major contributor to the failure. Chevrons are a pattern that is formed on a fracture surface that shows the direction of crack propagation, while pointing back towards the crack origin. The fracture surface displays these chevron markings (Figure 7). The figure also points to the fracture origin: the mounting hole. This further suggests that the incorrectly manufactured mounting hole is a factor in this failure.

Ductile Dimple in specimen

When observing fractures in metals, there are generally two mechanisms that are investigated. The first involves ductile behaviour and the second pertains to the brittle behaviour. Ductile behavior is when a material is able to experience large amounts of plastic deformation before catastrophically failing. In the case of the rifle under investigation, it is known that the barrel consists of 416R stainless steel. Different SEM images further show the presence of ductile dimple fracture (Figure 9).

Ductile dimple fracture has many different causations. One overwhelming agreed upon reason, for dimples occurring in materials that fail, is from the existence of void coalescence. A process called micro void coalescence can explain how void coalescence comes into existence. A void can nucleate then go through a growth process that eventually leads to coalescents, this greater coalescence eventually develops into the final fracture [13]. Furthermore, the presence of pores can contribute to ductile crack nucleation. In the rifle's chemical analysis, it is stated that the sulfur concentration is greater than the specifications (Figure 2). For this reason, it can be concluded that the structure of the metal is more prone to pores. The implications of pores can be made more devastating when debonding is considered.

The MnS inclusions that can be found in the SEM images also relate to the cause of fracture. These MnS "stringers" can be seen in Figures 4 & 5. A common observation in steels is fracture that is initiated by sulfide stringers [13].

The evaluation of the ductile existence in the SEM images suggest that particle spacing as well as size contributed to crack nucleation.

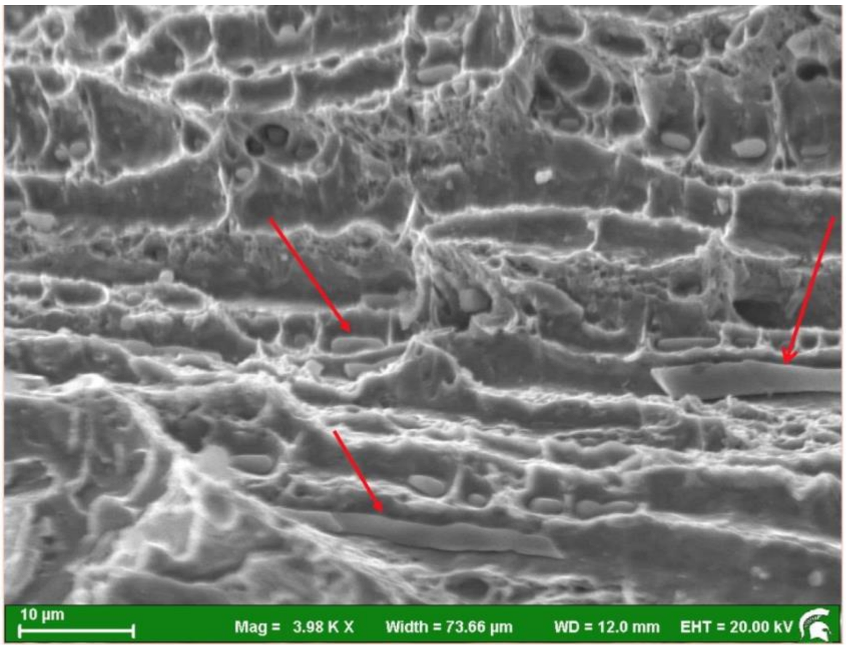

Figure 8: SEM image showing ductile dimples along with MnS inclusions. The dimples are elongated in the direction of the x-axis. This illustrates that the mode of failure is either mode II or III. These types of modes deal with shear or tearing.

Brittle & Intergranular in Specimen

The SEM images not only showed ductile dimple fractures but also showed intergranular fracture. Intergranular fractures are notably associated with brittle fractures. However, in ductile fracture conditions it is possible to have intergranular ductile dimple fracture. When observing intergranular fracture, it is important to look for a giveaway called rock candy conditions (Figure 9). Rock candy is just a comparison between the surface topography and how it looks like the old children candies. Once these shapes are examined on the surface, it becomes quite evident that intergranular fracture has occurred. This idea ties into the original MnS inclusions, as well. The MnS inclusion could have become stress risers and induced a crack that propagated repeatedly each time the rifle was discharged until eventually failing.

Another source of brittle fracture comes from the 416R steel phases. The steel used in the gun barrel is heat treated and later goes through temper embrittlement to form martensitic phases, where martensitic phases are known to be brittle. An error during heat treatment could be a culprit in the steel used in the barrel to not meet the required characteristics for the application it was intended for. If this is the reason the responsibility of the failure falls upon the manufacturer and not the user.

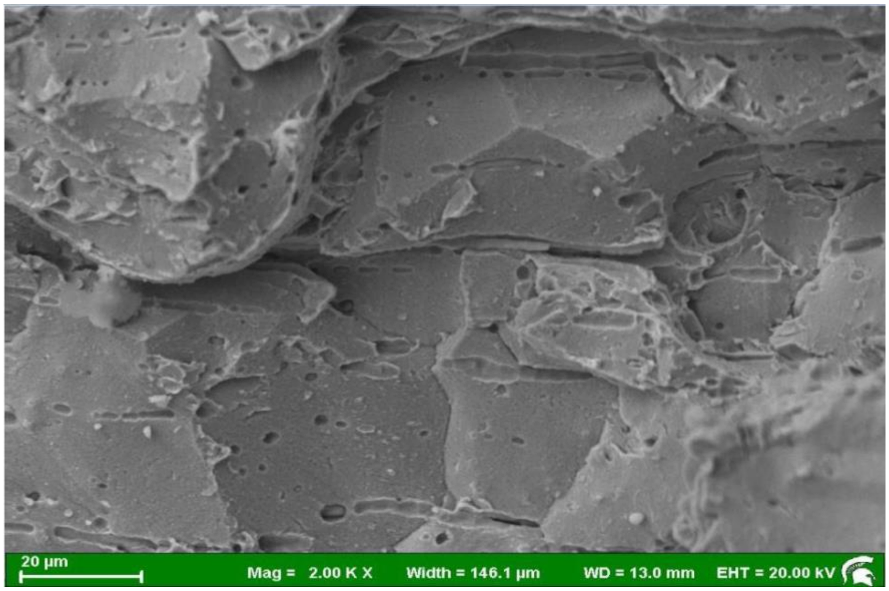

Figure 9: SEM image displaying the rock candy topography. This supports the theory that MnS inclusions as well as faulty temper embrittlement processes are likely the reasons the gun barrel fractured and failed.

Potential Human Impact

This failure had particularly dire consequences as the barrel split of this rifle caused severe body injuries to the user. But, the overall failure in design and manufacturing of this rifle could also have impacted other consumers in terms of permanent injuries, burns, and even deaths due to large barrel explosions. Such injuries to these consumers are directly correlated to financial losses. Consumers of this weapon could be forced into early retirement as they may be required to pay for the expensive surgical procedures and further rehabilitation.

Furthermore, legally, the gun manufacturing companies, in contrast to manufacturers of other consumer products, have the sole discretion to decide whether to recall a potentially dangerous weapon or not [12]. This creates a huge problem as without the recall of these improperly designed and manufactured weapons, such severe impacts will continue to increase in the future.

Conclusion

It is believed that the failure was the result of a number of errors being made by the manufacturer. After inspecting the fracture surface, the SEM images and the optical micrographs given, it was decided that the compounding effects of the improperly manufactured mounting hole, the incorrect chemistry for the 416R stainless steel barrel, and the anisotropic nature of the material used for the barrel ultimately led to the failure of the rifle.

This type of failure has extreme consequences and consumers deserve to have manufacturers that take these issues seriously by increasing quality control, and part inspection so that mistakes like the aforementioned are not made again. Final inspection needs to be adjusted such that a faulty part is not sent out to the market to ensure the safety of the consumers. Similarly, other stainless steels that show less anisotropic behaviour can also be used to create this barrel to further minimize failure.

Additionally, by simply keeping the hole depth and barrel chemistry within design specifications, this gruesome mistake may very well have been avoided and can be prevented in the future.

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