Failure Analysis of Large Alloy Steel and White Iron Castings

Robert B. Schrock
ME Global, Tempe, Arizona, USA

ABSTRACT

White iron and alloy steel mill liner castings as large as 5 tons are typically used in semi-autogenous grinding (SAG) mills, autogenous grinding (AG) mills, and ball mills to process mineral ores after primary/secondary crushing operations. Case histories will be presented on AG and SAG mill feed end/middle/discharge end head liners, shell liners, and discharge grates that either fractured prematurely or did not perform as designed in service. Details related to the process of metallurgical failure analysis will be discussed on these large castings with lessons learned to avoid future failures and minimize the risk of costly downtime.

Keywords: failure analysis, case history, white iron mill liners, alloy steel mill liners, mineral ore processing

INTRODUCTION

Alloy steel and white iron castings offer unparalleled strength, wear resistance, and versatility in a wide array of applications in the mining industry.[1] These materials have consistently demonstrated their utility in the face of extreme operational demands. Yet, like all engineering materials, alloy steel and white iron castings are susceptible to failure and the consequences of such failures can be significant, ranging from costly downtime to safety hazards.

The definition of failure is the inability of a manufactured part or assembly to perform its intended function for any reason during its service life.[2] Metallurgical failure analysis is a key discipline in materials science and engineering, dedicated to unraveling complex factors that contribute to the unexpected deterioration of components. In the case of alloy steel and white iron castings, the importance of robust failure analysis cannot be overstated. Understanding the origins and mechanisms of failure in these materials is indispensable for preventing future problems, optimizing casting processes, and ensuring the reliability of critical mining operations. Superficial evaluation of "broken casting pieces" is not sufficient in most cases to properly identify a cause of failure.

This paper describes the failure analysis process in the context of alloy steel and white iron castings. It will describe forensic methodologies employed in evaluating casting failures from initial inspection of fractured castings to identification of possible root causes, with a focus on the role of microstructural examination and material properties. Case studies are presented that explain complexities inherent with failure analysis that lead to valuable insights based on an understanding of metallurgy, material behavior, and casting processes.

APPLICATION AND ALLOYS

Mineral ore processing is a fundamental stage in the extraction of valuable minerals and metals from their naturally occurring ores. This crucial step in the mining industry involves a series of physical and chemical processes designed to liberate the desired minerals from the surrounding rock and impurities. The main objective is to maximize the recovery of economically valuable elements while minimizing waste generation and environmental impact.[2] A generic example of a comminution process is shown in Figure 1.

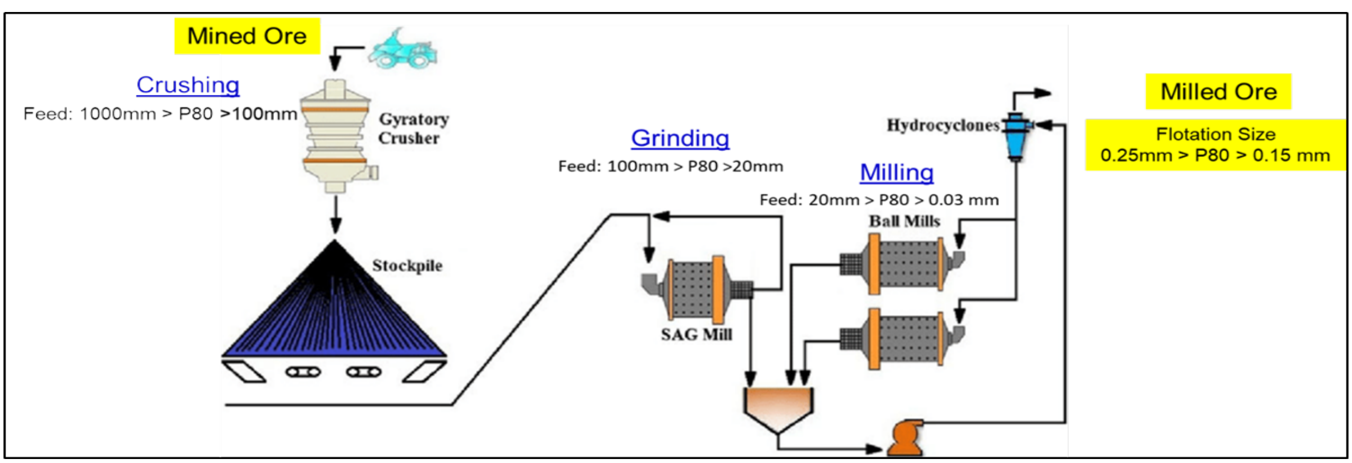

Figure 1. A generic process of mineral ore comminution. (Artwork courtesy of ME Global.)

Mineral ore processing encompasses several stages to achieve a specific particle size needed for concentration, where techniques such as flotation, gravity separation, or magnetic separation are employed to separate valuable minerals from gangue materials.

Primary and secondary gyratory crushing are the first comminution stages, followed by processing through rotational AG, SAG and ball mills. Primary/secondary crushing is typically performed using austenitic manganese alloys which are not discussed in this paper.

Grinding ball media are mixed with mineral ores in SAG and ball mills. No grinding media are used in AG mills. Figures 2, 3, and 4 show typical alloy steel liner castings installed in AG and SAG mills and white iron liner castings installed in ball mills. Water slurry containing mineral ore enters the feed end, is ground within a circumferential row of shell liners, and exits at the discharge end. Each liner has a wear side impacted by grinding media and mineral ore and a fit side that mates to the mill shell wall. A central lift feature scoops ore and grinding media to a desired height which then falls onto flat plate areas of the liners where ore is crushed. Liners will be gradually consumed by abrasive wear and need to be replaced after a designed service life. Liners that experience cracks, fractures and high wear rates in service are regarded as failures.

Figure 2. An example of alloy steel liners used in a SAG mill. (Artwork courtesy of ME Global.)

Figure 3. An aerial image of a ball mill. (Artwork courtesy of ME Global.)

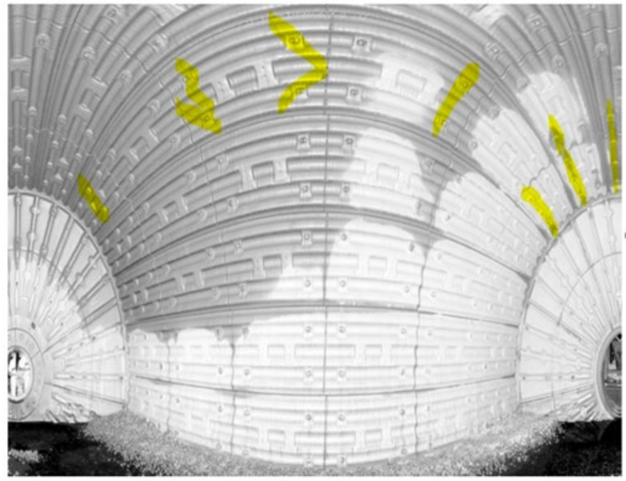

Figure 4. Wide angle view of a ball mill interior with fractures identified in yellow. (Artwork courtesy of ME Global.)

Alloy selection is critical to maximize service life during all stages of mineral ore processing. Cr-Mo alloy steel types used at ME Global for AG and SAG mills are described in ASTM A781.[4] White iron alloys for ball mills are described in ASTM A532 Class II – Type B.[5] Pearlitic Cr-Mo alloy steel microstructure is shown in Figure 5 and high chromium white iron microstructure is shown in Figure 6. These micrographs show typical wear surface cross sections from worn liners that successfully exceeded their designed service life.

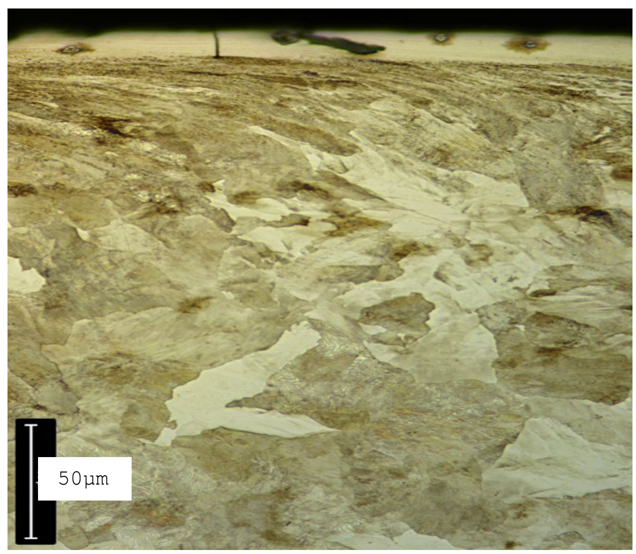

Figure 5. Cr-Mo alloy steel microstructure with deformed pearlite along the wear surface. 2% Nital etch.

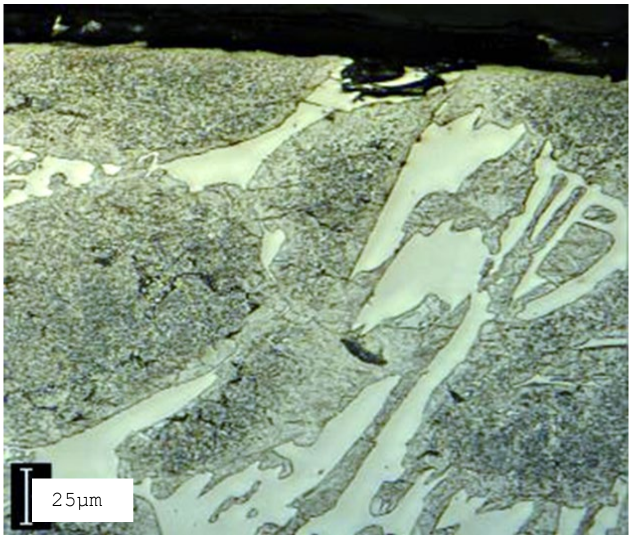

Figure 6. White cast iron microstructure along the wear surface consisting of primary eutectic carbides in a martensitic matrix containing small secondary carbides. 2% Nital Etch.

FAILURE ANALYSIS PROCESS

When conducting a failure analysis, attention to detail is paramount. A detailed forensic approach ensures that, even years down the line, reviewers of the report will have a comprehensive understanding of the methodology and actions undertaken during the analysis. Timely responses are a customer expectation, and proficiency in the failure analysis process improves analysis skills with each case. A written failure analysis report should be provided for review in a timely manner. However, thorough analysis and accurate results should be the primary focus. A summary of steps used in the failure analysis process is shown in Figure 7.

In-Field

- Visual Examination (non-destructive)
- Background
- Photography
- Shipment to analysis site

Laboratory

- Visual examination
- Photography
- Material analysis (destructive)
  - Sectioning of critical locations
  - Material Testing
    - Chemistry
    - Hardness
    - Impact
  - Microstructure
    - Metallography
    - Optical microscopy
    - SEM/EDS

Report

- Compile relevant findings in a draft report
- Determine failure mode and make conclusions based on available evidence
- Recommendations
- Review
- Final Report

Figure 7. Basic steps used in the failure analysis process.

IN-FIELD

Visual examination is the most important aspect of any failure analysis investigation and is a required first step at the in-field site. Many customer mines are remote, and it is important to collect relevant on-site background information up-front. This information is critical in determining causes of failure. Important information may include but is not limited to:

- Photos of parts & failure location within mill.
- Standard/Non-standard operating conditions.
- Overall mill condition/appearance.
- Fit-up assembly process.
- Bolt tightening process and torque levels.
- Run time of part/service life.
- Throughput of material & ball charge level.
- Material being processed.

In many cases, the individual conducting the failure analysis is not the same person that observes the failure at the customer site. This makes gathering critical information difficult at times. Good quality in-field photographs are important to tell a comprehensive story. Customer removal of failed castings and proper material shipping/handling to a qualified laboratory is crucial to avoid post fracture damage of broken pieces. Failure analysis is similar to forensic analysis of a crime scene. Contamination of fracture faces and poor documentation of part condition will hinder the failure analysis process and could lead to incorrect root cause determination.

LABORATORY

Once the failed casting(s) or fractured piece(s) arrives at a qualified laboratory for analysis, it is important to take "as-received" photos of all parts and conduct a detailed visual examination. Documentation of every relevant observation makes writing the final report much easier. Casting traceability and proper documentation of broken pieces can be a difficult task with large castings, but this information is critical for investigation of processing records. As always, safety must be a top priority. Measurement rulers and/or tape measures need to be included in all photos to document sizes and locations of all features in the image.

Red oxide rust and debris may be coated on fracture surfaces due to prolonged post-fracture exposure to the environment. Wherever possible, these coatings must be removed to expose fracture surface features. After fractures are clean, the next important step is to take photos of the castings once again. The images of the overall casting may reveal obvious features that help tell the story of what happened. Examples of this include excessive abrasion loss, gouging, and grinding ball "peening" impact damage. Photos of casting identification serial numbers, drawing numbers, and manufacture dates provide production history traceability.

Fracture features can be best exposed and photographed using oblique diffuse lighting. This illumination may reveal fracture initiation sites. In some cases, fracture faces may be severely worn post-fracture and initiation sites cannot be revealed. Knowledge of how the liner was used in service may help determine critical areas for analysis when fracture features cannot be revealed.

The next step is destructive sectioning and material property testing of the casting at critical locations. These locations may include fracture initiation sites but also areas away from the fracture. Due to the large size of these castings and timeliness associated with the failure investigation process it is important to develop a sectioning plan that can deliver the highest level of information in the shortest possible time. Only critical locations must be investigated. All sample sections must be large enough for chemical analysis, hardness measurement and microstructural examination. Other samples may be needed for impact testing or wear rate measurement.

At ME Global–Tempe, chemistry is determined by optical emission spectroscopy (OES) according to ASTM E415. Laboratory Brinell (HBW) hardness profiling near and away from the fracture is performed according to ASTM E10 using a 3000 kg applied load and a 10mm diameter tungsten carbide indenter.

Standard metallographic sample preparation according to ASTM E3 is critical for examination of alloy steel and white iron microstructures. Samples do not need to be mounted but mounting is recommended for preservation of edge features. Cross sections can either be hot or cold mounted in appropriately sized molds. Standard procedures for metallographic grinding and polishing should be used to ensure consistent results every time.

Samples should be manually examined by optical microscopy at low magnification in an as-polished condition prior to etching. This is done to reveal microporosity and inclusion features that may be obscured by etching. A 2% Nital etch works well to reveal microstructural features in alloy steel and white iron castings. Digital images acquired over a 12x – 1000x magnification range have sufficient resolution to reveal fine features and identify metallurgical phases present in alloy steels and white iron. All micrographs must contain a scale bar to show the approximate size of features contained in the image. Small amounts of microporosity and inclusions are typically found in all castings and are not necessarily the root cause of a failure.

Two other analytical techniques that are often used in failure analysis are scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDS). High resolution SEM digital images can reveal fine features on fracture surfaces. Atomic number contrast Backscatter Electron (BSE) images are typically used to reveal microstructural phases and inclusions. X-ray EDS microanalysis is commonly used in failure analysis for qualitative elemental analysis across an acquired image field, but it can also be used to obtain semi-quantitative results at localized areas. Combining SEM and EDS microanalysis methods can be used to characterize specific locations at fracture initiation sites.

REPORT

Fact-based report writing in failure analysis holds great importance as it serves several critical functions. It documents the entire investigative process, providing a clear and comprehensive account of the methods, findings, and conclusions. This documentation is essential for transparency and accountability, ensuring that all stakeholders have access to the same information. The document should flow coherently and effectively communicate the process, issues, and proposed solutions to non-experts. Failure analysis reports serve as valuable learning tools. They capture the lessons learned from each failure investigation, helping organizations improve their processes and avoid repeating the same mistakes. They can serve as essential documentation in legal disputes, insurance claims, and compliance with safety and quality standards.

In the report-writing process, the initial step involves a meticulous analysis of all collected data, followed by the compilation of pertinent findings into a preliminary draft report. This pivotal stage empowers the analyst to discern the failure mode and draw conclusions based on available evidence. Recommendations should be made to prevent a recurrence of the same issue. A thorough review of the report by all stakeholders prior to finalization serves as a critical quality assurance step to ensure all aspects of the failure have been considered.

WHY EXAMINE CASE STUDIES?

Case studies provide real-world examples of many factors that can lead to failures in castings. Every failure analysis is both unique and similar. These practical examples offer a unique opportunity to dissect the root causes, from material defects to design flaws or operational errors, and to gain insights into how such issues can be prevented in the future. Forensic analysis skills are acquired over time. Learning how past experiences may apply to today’s problem makes it easier to determine possible root causes. Case studies also serve as powerful teaching tools, allowing engineers to learn from past mistakes to minimize risk and improve decision-making.

Case histories related to alloy steel and white iron mill liners typically fall into the following categories: excessive wear damage in service; installation issues; accidental customer damage; casting defects; casting design; improper alloy selection; and heat treatment.

CASE STUDY 1: FRACTURED WHITE IRON LINERS FROM AG MILL

A 32' diameter x 13' long AG Mill at a copper mine had newly installed white iron head liners that fractured after several hours in service. Nineteen fractured liners were identified. Due to customer time constraints, five liners were selected for failure analysis. The nineteen fractured liners included five different part designs and one sample from each design was selected. All nineteen fracture faces were examined & photographed prior to sample selection.

FINDINGS

Bolt hole shoulders showed evidence of wear damage indicating possible alignment issues during installation. Excessive bending stresses imposed on the fit side may have been caused by mill shell mating surface conditions, mill shell fit-up and bolting procedures during installation.

Fracture morphology indicated all fractures initiated from the fit surface of each casting. Fractures were brittle in nature, which is typical for white iron, and initiated either near a bolt hole or at locations of high stress as shown in Figures 8 and 9.

At locations similar to the ones shown in Figure 10, each analyzed sample had chemistry, hardness, and microstructure within specification for heat treated white iron castings. No evidence of entrapped debris, abnormal microporosity, or large inclusions were found near the initiation sites that would have facilitated crack initiation.

RECOMMENDATIONS

Previous investigations at this copper mine have shown head liner castings have historically fractured in a similar fashion. All breakages occurred soon after installation and initiated from the fit side. To avoid the risk of future failures, recommendations were to review all aspects of the installation process including visual examination and laser scanning of mill shell mating surfaces, laser scanning mill liner fit surfaces prior to installation, and reviewing bolting procedures. Note that similar breakages of head liners were previously occurring in another AG mill at the same copper mine, and a re-designed head liner was produced and installed which eliminated breakage. The same redesigned head liner could be installed in this mill.

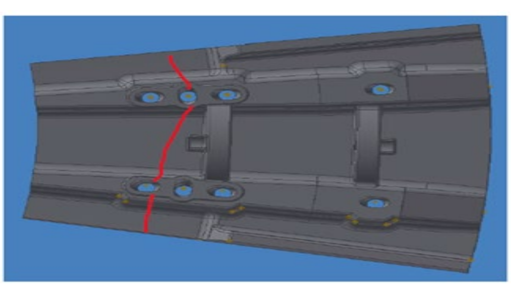

Figure 8. Drawing indicating fracture location.

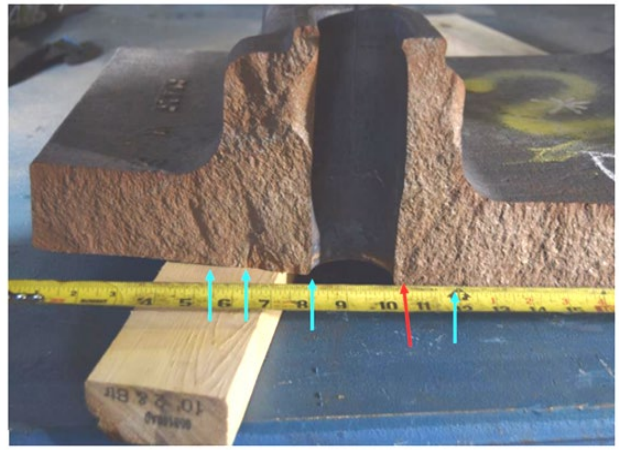

Figure 9. Locations of high stress on the fit side of a head liner near the bolt hole.

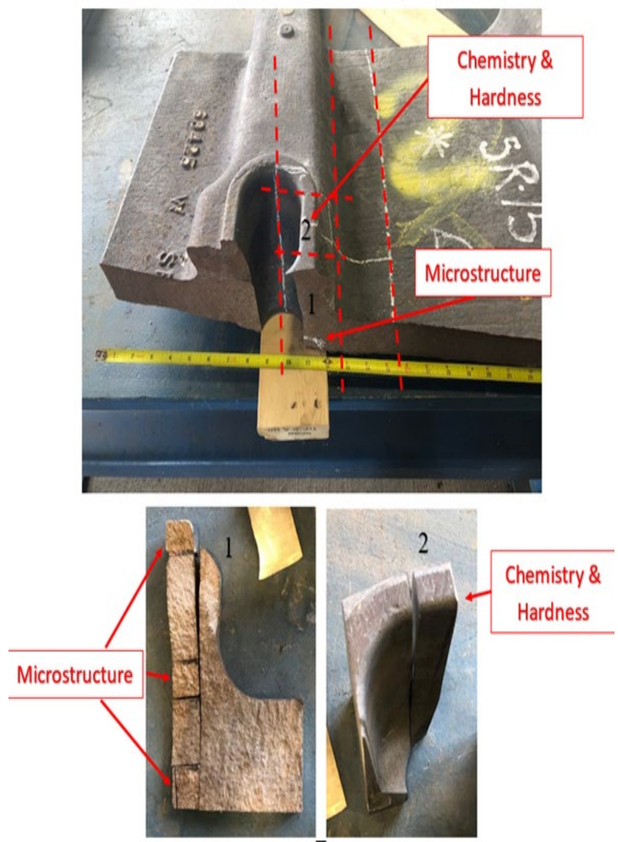

Figure 10. Sectioning and locations for chemistry, hardness and microstructure analysis.

CASE STUDY 2: WORN ALLOY STEEL SAG MILL MIDDLE LINERS

A 28’ diameter x 15’ long SAG mill at a precious metal mine had several rows of alloy steel middle shell liners that experienced significant wear on one side of the liner during the final month of service life. No fractures had occurred. One liner was selected for failure analysis. Mine site admitted the mill was operated under abnormal service conditions near the end of service life.

FINDINGS

Abnormal wear was likely caused by the milling environment and was not attributed to casting quality.

Middle shell liner production records for the liner serial number submitted for analysis did not reveal non-conformances that would have contributed to accelerated and uneven wear in service. Chemistry, surface hardness and nondestructive testing (NDT) inspection results reviewed by the foundry all showed conformance to alloy specification and inspection requirements. Uneven wear shown in Figure 11 did not occur on feed end or discharge end alloy steel liners that also met quality specifications. No abnormalities were noted by visual inspection.

As shown in Figure 12, microstructures of the thickest and thinnest sections of the casting consisted of fine pearlite consistent with properly heat treated alloy steel castings. Through-hardness and chemistry of these sections were typical for this alloy.

RECOMMENDATIONS

No obvious cause for the accelerated wear could be determined. Abnormal mill operation by the customer should be avoided. Design modifications to increase lifter height could be considered to extend mid shell liner service life.

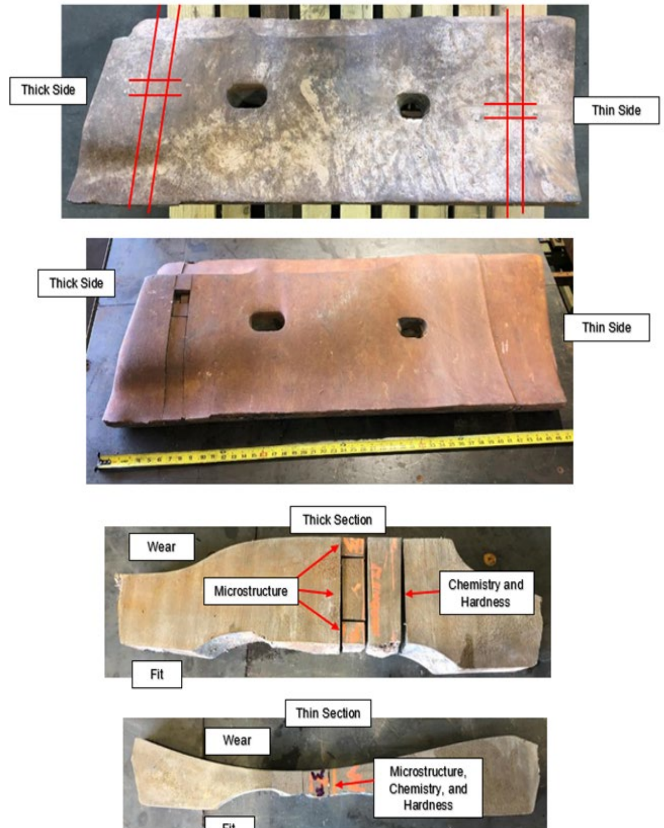

Figure 11. Wear profile, sectioning plan and sample locations.

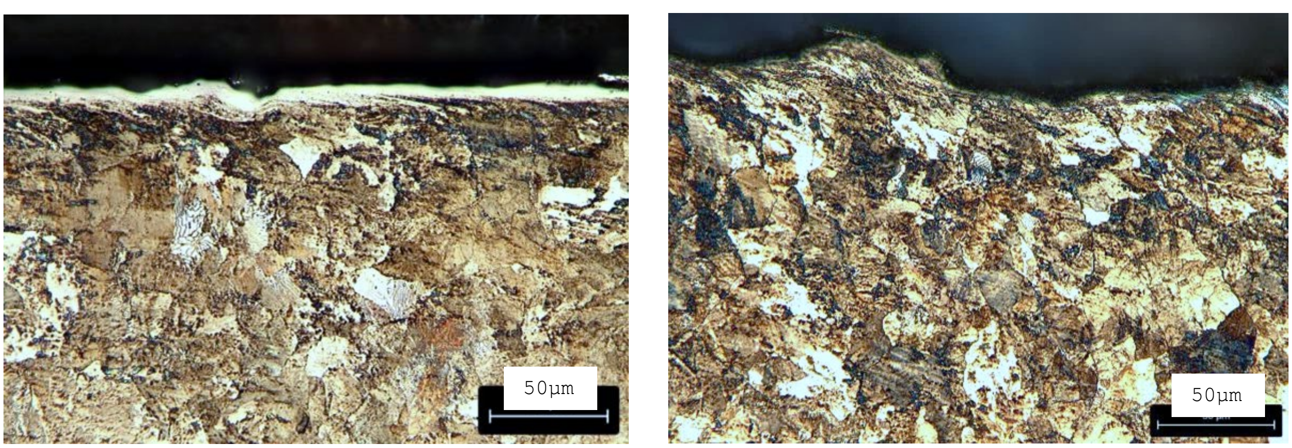

Figure 12. Thick Section wear surface (Left) with small white surface layer of untempered martensite formed by abrasive wear in service along with deformed pearlite, and Thin Section wear surface (Right) showing a smaller layer of deformed pearlite. 2% Nital Etch.

CASE STUDY 3: FRACTURED AG MILL WHITE IRON LINERS

A 36' diameter x 20' long AG mill at an iron ore mine had six white iron inner feed end head liners that fractured at 50% design life. Two liners randomly selected for failure analysis had similar fracture features compared to the other failed liners.

FINDINGS

A combination of entrapped sand particles and non-martensitic phases at locations of high stress likely facilitated crack initiation. Cracking extended through weaker areas of the casting until reaching either a surface or a non-compromised region within the casting.

Both head liners selected for analysis had similar fracture features with several crack initiation sites around bolt holes on the fit surface. Some cracks did not run completely through the casting and had to be opened for inspection as shown in Figures 13 and 14. No obvious abnormalities were noted by visual inspection. Fracture initiation sites and fracture directions were random through plate and lift areas. Figure 14 shows fracture fronts either changed directions during propagation or multiple fronts converged, resulting in parts having multiple fracture faces on different planes.

Production records did not show non-conformances for inner liners produced and shipped against this order. Production records did, however, show an abnormally high internal scrap rate during this production run. Chemistry, surface hardness and NDT inspection of shipped castings showed conformance to white iron specification and inspection requirements.

Both analyzed liners had bulk chemistry within specification requirements. One liner had through-hardness typical of heat treated white cast iron, while the other liner had lower than normal through-hardness near the fit surface attributed to the presence of non-martensitic phases and non-metallic inclusions.

As shown in Figures 16 and 17, microstructure consisted of tempered martensite and eutectic carbides typical of heat treated white cast iron. However, high amounts of non-martensitic phases (pearlite + bainite) were noted throughout both castings, which may have weakened the microstructure. Figure 18 shows entrapped sand particles identified by energy dispersive X-ray spectroscopy (EDS) microanalysis which also may have weakened the microstructure near bolt hole fracture initiation sites.

RECOMMENDATIONS

Sources of entrapped sand should be investigated and eliminated. Improvements in heat treatment should be investigated to minimize the presence of non-martensitic phases.

Perform additional sampling of feed end inner head liners during the next production run, including destructive testing, as it is unlikely that standard NDT inspection methods will detect entrapped sand particles due to their relatively small size and random distribution.

Figure 13. Image of white iron casting where fracture occurred. Casting had to be broken open to expose the fracture face.

Figure 14. Sample locations used for microstructure examination. In-service fracture is slightly discolored compared to laboratory fracture to expose the crack.

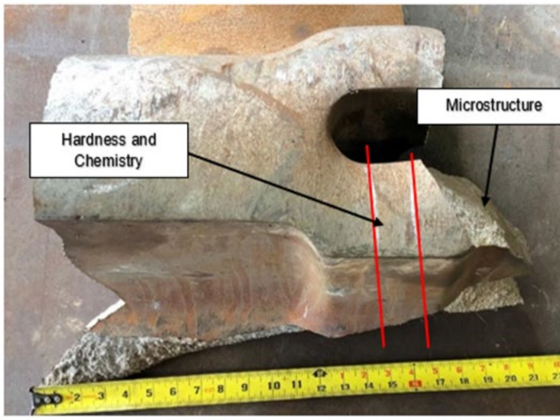

Figure 15. Sectioning plan for analysis.

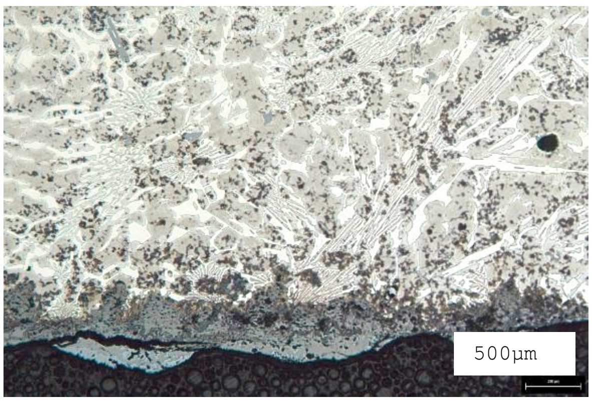

Figure 16. Optical micrograph of white iron containing dark-colored non-martensitic phases. 2% Nital etch.

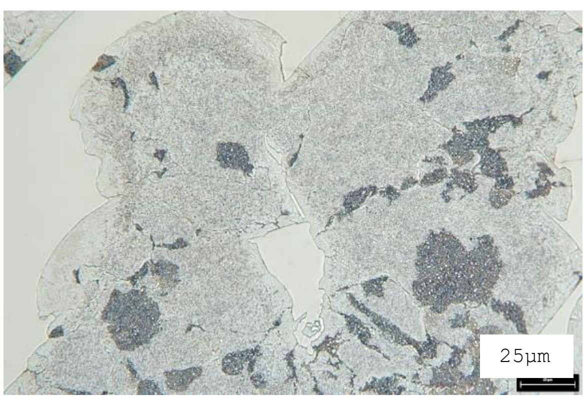

Figure 17. Optical micrograph of white iron containing non-martensitic phases. 2% Nital etch.

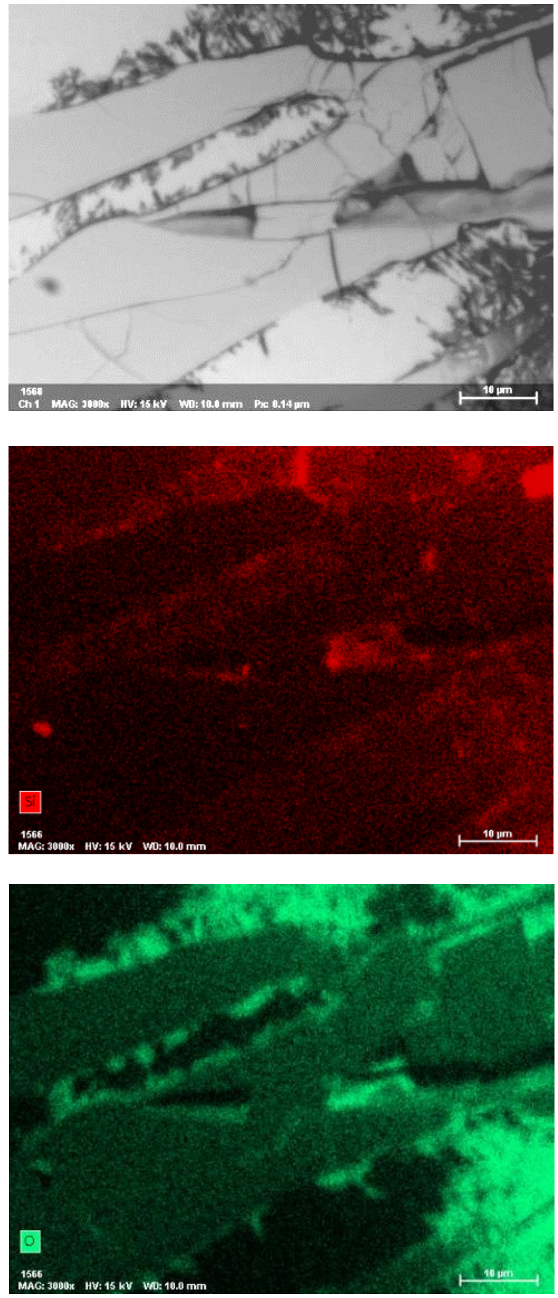

Figure 18. Backscatter electron image of white iron containing entrapped sand & X-ray EDS maps of silicon and oxygen.

CASE STUDY 4: FRACTURED ALLOY STEEL DISCHARGE GRATE

A SAG mill at an iron ore mine had a cracked alloy steel discharge grate that was removed and replaced during a scheduled relining operation. The grate cracked through its webbing along the leading edge at an unknown time during its service life.

FINDINGS

Cracking shown in Figure 20 was attributed to overload imposed on the discharge grate rib which had a higher hardness than specified for heat treated alloy steel grates. Higher hardness was attributed to bainite seen within the pearlite microstructure.

Mixed bainite/pearlite shown in Figures 21 and 22 is undesirable for discharge grates since this microstructure is expected to have lower fracture toughness compared to fine pearlite. Lower fracture toughness can facilitate crack initiation and overload fracture from impact loading imposed on the grate rib in service. Heat treated alloy steel grates are specified to be fully pearlitic with lower hardness and greater impact resistance.

The presence of bainite indicated the grate ribs rapidly cooled during heat treatment to a lower than desired temperature after austenitization. Bulk chemistry was within specification for alloy steel castings.

RECOMMENDATIONS

Review heat treatment procedures and practices to ensure ribs and all other locations on discharge grates have hardness and microstructure within specification. Selecting alternative locations for monitoring still air-cooling temperature on grate castings, and packing rib slots with Kaowool™ ceramic insulation, could help achieve the desired results.

Figure 19. As received casting for failure analysis.

Figure 20. Fractured alloy steel grate rib showing fracture features. Arrows indicate overload fracture initiation site.

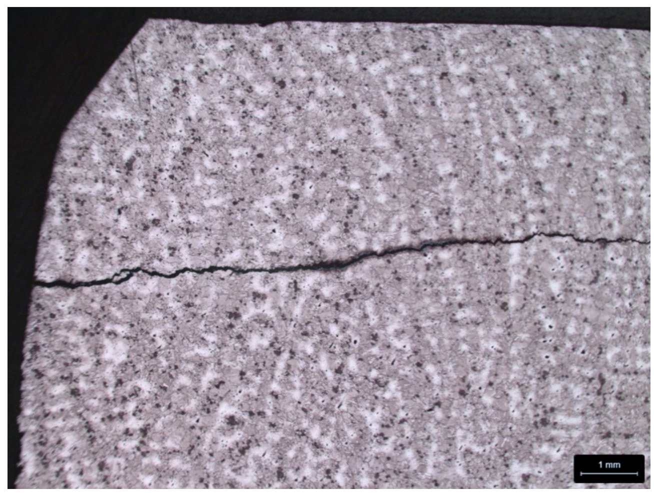

Figure 21. Undesired microstructure of pearlite + bainite in a cracked alloy steel grate rib. 2% Nital Etch.

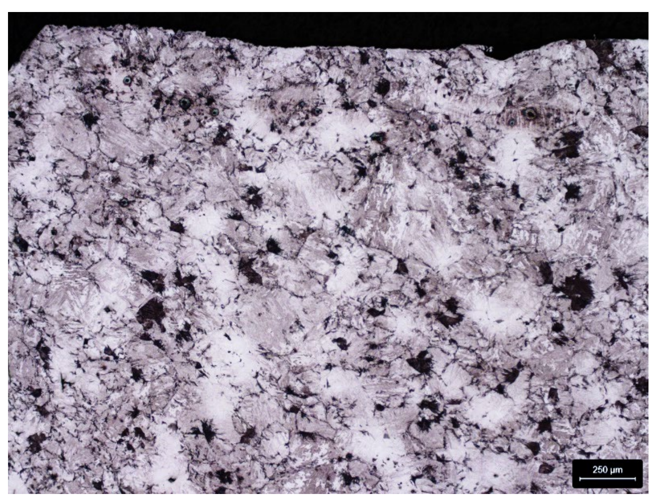

Figure 22. Undesired microstructure of pearlite (dark) + bainite (grey) at the wear surface of a cracked alloy steel grate rib. 2% Nital Etch.

CONCLUSION

Visual examination is the most important aspect of any failure analysis investigation and is a required first step. Through proper use of failure analysis and forensic methods it is possible to draw correct conclusions and make recommendations based on relevant background information and fact-based evidence obtained from material testing and metallographic examination. Logical progression from a "macro" understanding of background information and visual examination to a "micro" understanding of localized microstructure and material properties is required for all investigations.

Large part sizes and complex patterns associated with alloy steel and white iron liner castings used in mineral ore processing can be handled safely and appropriately to ensure the traceability of all sectioning and destructive material testing. Proper documentation throughout the entire analysis process is necessary to prevent additional wasted time and effort, and facilitate report writing. Detailed reporting provides a written record of the failure event and is required for further review to identify root causes and make corrective actions to minimize the risk of future failures.

ACKNOWLEDGMENTS

The author thanks Dan DeMiglio and Scott Haines for their support and supervision and ME Elecmetal-Tempe for their services.

REFERENCES

1. Monroe, R., & Poweleit, D., "Steel Casting Mechanical Properties," Steel Founders' Society of America, Crystal Lake, Illinois. https://www.sfsa.org/sc3/downloads/Steel%20Casting%20Properties.pdf (Link last accessed 01-16-2024.)
2. Brooks, C.R, & Choudhury, A., "Failure Analysis of Engineering Materials," (n.d.). McGraw Hill Companies (2002).
3. Comminution (2019) Multotec, available at: https://www.multotec.com/en/comminution (Link last accessed 04-03-2024.)
4. ASTM Standard A781/A781M-21, 2021, "Specification for Castings, Steel and Alloy, Common Requirements, for General Industrial Use," ASTM International, West Conshohocken, PA (2003). DOI: 10.1520/A0781_A0781M-21, https://www.astm.org/ (Link last accessed 04-03-2024.)
5. ASTM Standard A532/A532M-10, 2019, "Standard Specification for Abrasion-Resistant Cast Irons," ASTM International, West Conshohocken, PA (2003) DOI: 10.1520/A0532_A0532M-10R19 https://www.astm.org/ (Link last accessed 04-03-2024.)
6. Ngqase, M., & Pan, X., "An Overview on Types of White Cast Irons and High Chromium White Cast Irons," *J. Phys. Conf. Ser.* 1495 012023. https://iopscience.iop.org/article/10.1088/1742-6596/1495/1/012023/pdf (Link last accessed 04-03-2024.)
7. William T. Becker and Roch J. Shipley, editors, ASM Handbook, Volume 11, "Failure Analysis and Prevention," ASM International Handbook Committee, Materials Park, Ohio, ASM International (2002). https://www.asminternational.org/ (Link last accessed 04-03-2024.)