Critical Assessment: Forensic Metallurgy – the difficulties

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Abstract

Forensic metallurgists are asked to address failures across a wide range of materials, length-scales and applications. This requires in-depth knowledge of metallurgical principles, manufacturing and engineering fields. The metallurgist will be asked to determine whether or not the appropriate engineering or quality standards have been followed – and this may be the Standards that were in place at the time of manufacture, not those currently in place – and whether the failure results from use or abuse. The paper reviews how these skills have been applied to a range of historical and contemporary cases involving failure and discusses some of the issues that are important for determining the root cause of a problem. Some difficulties in current approaches are also presented.

Introduction

Forensic metallurgy is part of the field of forensic engineering which applies engineering science to issues that relate the investigation of unforeseen failures, crashes, disasters or other incidents. The term "forensic" strictly means in application to a court of law and implies that there may be a criminal aspect to the issue at hand but could also imply negligence or breach of contract[1]. The result of a forensic investigation typically involves the preparation of technical engineering reports, and may require giving testimony and providing advice to assist in the resolution of disputes affecting life or property.   Often, the outcome of forensic investigations is agreed before resolution in court is required. In this paper, and indeed in the literature more broadly, "forensic" is (mis)interpreted as the application of forensic techniques to the investigation of materials, products, structures and components that have either failed in service or have failed to perform as intended. So, for example, the work of Lewis et al.[2] often contains case studies where the analyses were used as evidence in legal proceedings, but references to "forensic" engineering often refer simply to a failure analysis that may never be exposed in legal proceedings.

A forensic investigation in an industrial context may involve understanding how products or components could be redesigned to eliminate future failures. Forensic metallurgy is used to determine how materials fail across many different length scales, from understanding why a connect has failed in a microelectronic device using high resolution transmission electron microscopy or atomic force microscopy,[3] to determining whether coins are counterfeit,[4,5] to understanding how the composition of the steel in the Titanic may have influenced the failure[6,7] or why the World Trade Centre collapsed on the 9th September 2001[8]. Forensic metallurgy is also a routine tool used by manufacturers to understand how metals are performing in service and for life extension purposes in for example steam or nuclear power plant. The metallurgical analysis may often be combined with additional analysis of the expected stresses and loading on any component[9,10].

A range of questions can be asked during a typical metallurgical failure analysis such as:

- At the point of first use of the product did it meet the design specification? Did the mechanical properties of the material meet the design specification? Were the chemical and microstructural properties of the material as anticipated?
- Were there flaws in the product from the original manufacture?
- Were there issues with the original design of the product/component/structure?
- Were the designed properties for the material sufficient for the loads/temperatures/environments that the product experienced in service?
- Is there evidence that correct maintenance had been carried out during the lifetime of the component?
- Is there evidence that there was incorrect operation of the component either deliberately or accidently (over-torqueing for example)? Had the specified design life been exceeded?
- Had the component been adequately serviced or inspected?

Further details of failure mechanisms and specific issues related to failure analysis can be found in e.g. Lewis *et al*., 2003[2], ASM,1987[11], Wulpi, 1999[12], Hainsworth and Fitzpatrick 2007[13], Ross, 1995[14]. The purpose of this article is to assess the current state-of-the-art in forensic metallurgy and highlight challenges for future progress in this field.

One of the difficulties in any forensic investigation for a particular specialist is that the root cause of the failure may not be linked to their specialism. The metallurgy may be irrelevant, for example, if the component has been used inappropriately or overloaded: in which case a metallurgical assessment simply shows that the product was manufactured to specification. For example, the author has personally conducted forensic assessment of many ladder failures, and in all cases the failure was from abusive loading rather than any problems with the metallurgy of the ladders. Occam's razor, where "*Among competing hypotheses, the one with the fewest assumptions should be selected*", is often a good starting point for any analysis. Metallurgists need to think carefully before embarking on expensive testing if the result is not likely to be of practical benefit.

Dr Ken Reynolds of The Open University used to tell the anecdote of an incident early in his career working in a pipe mill in the West Midlands. There was an intermittent problem with pipes cracking during the final drawing stage, that had baffled many eminent metallurgists, whose best diagnosis was segregation of alloying elements under gravity whilst the pipes were stored vertically between processes. The real reason became apparent when Reynolds took a short cut through the annealing plant to the canteen one rainy evening, and came across an operative cooking bacon on a shovel: he had opened the furnace door to do so and hence the pipe ends were not at temperature. So the problem was intermittent because this would only happen when that particular operative was on the night shift and had bacon for his supper!

Initial inspection

An initial examination of a failed metallic component will often indicate the mode of failure. A visual inspection will look at the general shape and colour of the component and whether or not wear, corrosion or pitting is apparent, any obvious features such as large inclusions or porosity, or evidence of gross damage or abuse of the specimen. After the initial analysis,

additional higher magnification lenses or loupes, stereo microscopes, or scanning electron microscopes will be used to examine the fine detail of the fracture surfaces of the failed component. It is important to properly preserve any fracture surfaces for detailed examination[15]. The initial examination will help to determine the root cause of the failure be it overload, creep, fatigue, corrosion or wear[11,16] although additional investigation of the composition, microstructure and mechanical properties may be required to definitively define the mechanism.

Composition: Determining the Chemistry

Often, one of the first questions in any investigation of a metallurgical failure is whether or not the material being investigated is of the intended chemical composition. In order to determine the composition of the material a number of techniques may be used. A first analysis might be undertaken using energy-dispersive X-ray analysis in the scanning electron microscope[16] which gives the main components but is generally not helpful for quantitative analysis of light elements (below atomic number 11). For an accurate quantitative analysis of the material in question a flat polished area of the material should be examined[17]. Clearly, in order to determine the bulk composition, it is important that a representative area of the material is examined. Sometimes this can be extremely challenging in cases where it is not possible to destructively section part of the component or where the fragment of retrieved material is small. Quantitative chemical analyses where destructive analysis is possible are typically performed by spark optical emission spectroscopy (Spark OES), inductively-coupled plasma optical emission spectroscopy (ICP OES), or X-ray Fluorescence (XRF)[18]. These give information on the chemistry but not the phase: for phase information X-ray diffraction (XRD) is the most used technique[19]. The exact choice of analysis technique depends on type of sample and the quantity of material available. XRF and Spark OES are the least destructive to the sample as long as it fits into the instrument. Other wet chemistry or combustion techniques are also possible[18].

Composition is also important for analysing dust and debris in a variety of engineering failures. Debris analysis was performed after the collapse of the World Trade Centers in 2011. The composition was found to be that of the steel debris and protective paint coating used on the structural steel girders by using EDS and FTIR respectively. Analyses such as these are important in determining that the dust cloud that covered Lower Manhattan was caused by the building collapse[20-22] and not by other means. The analysis of volcanic ash and dust and its impact on engine failures[23-27] was also critical in the decision to ground airplanes when Eyjafjallajökull in Iceland erupted in 2011 causing $2bn in economic losses to the airline industry and six days of travel disruption.

Analysing the microstructure

Many of the desired mechanical properties of materials are achieved by applying specific thermomechanical treatments to components. An examination of the microstructure can determine whether these treatments have been appropriately applied. Grain-sizes and shapes can be determined by metallographic analysis to see whether a specific average grain size was achieved. The analysis of grain size and shape can be determined by

traditional linear-intercept methods such as those defined in the ASTM standards[28] or by techniques such as Electron-Back-Scattered diffraction[29]. The shape of grains will help to determine whether or not the appropriate cold-working processes were applied (flat pancake shape grains indicating cold-rolling for example) and whether or not the material was cast or forged[3]. Precipitate distributions can also be examined. Typical questions in this area might be: are the precipitates dispersed throughout the grains or collected at grain boundaries?; and are they the optimum size and shape that would be expected? Precipitate chemistry and shape can be useful in indicating the thermal history of a specimen whether or not that is a temperature that has been exposed to high temperatures for long times in e.g. alloys used in steam power plant[30] or whether an aluminium alloy used in an aerospace application has been optimally aged[31].

Physical Properties

In order to understand whether or not a material failed because it was not sufficiently robust for the application, it is necessary to conduct an assessment of the mechanical properties of the material. This can be challenging if the fragment of material that is retrieved is small. The key mechanical properties are usually strength and toughness. In order to determine the strength of the component, the first tool that is often used in failure analysis is hardness testing, where indentations are made into the material using an indenter of known geometry and a known applied load. The hardness of a material can be related to its strength by a simple empirical relationship (for example for Vicker's indentations, $H \approx 3\sigma_y$ where H is the hardness and σ_y the yield stress)[32]. The hardness test may subsequently be followed up by more accurate testing if the hardness is not as anticipated.

A material's toughness is more difficult to determine from small samples. The toughness of a material is a measure of its resistance to crack growth and there is often a conflict between developing materials that are both high strength and tough[33,34]. Toughness is also difficult to ascertain from an inspection of a failed component as whether or not a material may exhibit a ductile or a brittle fracture can be affected by the geometry of the component, with plane strain conditions in large samples leading to brittle failures in materials that would otherwise be considered as "ductile"[35].

Sometimes more detailed knowledge of mechanical properties such as fatigue life are required. A major failure of railway track occurred at Hatfield in 2000[36-38]. The cause of the failure was gauge-corner cracking caused by rolling-contact fatigue and the track broke into over 300 pieces over a distance of approximately 35m. Inspection of the wider UK rail network showed that there were an additional 2000 sites with potentially dangerous cracks. This incident demonstrated that regular inspection, and more importantly reacting to the information obtained from inspection, is critical in preventing failure.

Many companies use rigorous non-destructive testing techniques to look for defects, such as dye penetrant, radiographic, eddy current or ultrasound inspection. In the aerospace industry for example, immersion ultrasonic inspection is widely used for investigating whether or not flight-critical parts contain defects[39]. The inspection looks at wall thickness,

surface and internal defects and discontinuities and determines whether a part is suitable for use. Rigorous inspection is important for eliminating failure ahead of time.

Failure from Environmental Factors

Many metallic materials that are subjected to high temperatures and/or wet and moist environments will suffer from oxidation and corrosion. Corrosion/oxidation failures can be prevented by good design and regular maintenance. One particular area of corrosion failure that can lead to unanticipated failures is stress-corrosion cracking. In order for stress-corrosion cracking to occur there must be a specific chemical environment and a tensile stress present. One of the earliest examples of stress-corrosion cracking (or season cracking) was in the failure of British Forces brass cartridges stored in stables in monsoon season in India. The cracking was found to be caused by ammonia from horse urine and residual stresses left over from the cold-drawing process used to form the cartridges[40]. A more recent example where stress corrosion cracking was found to be an issue is in aluminium aircraft landing gear[41]. The necessary stress can arise from residual stresses introduced during manufacture of the component (from e.g. hole drilling and reaming), cyclic differential expansion and contraction of the landing gear components, or the repeated application of mechanical force on landing. Aluminium alloys are susceptible to stress corrosion cracking by chlorides which can be present from moisture from flying over a marine environment.

Another type of environmentally-assisted cracking is hydrogen embrittlement. In 2014, a number of bolts failed on the Leadenhall "Cheesegrater" Building in London. Laing O'Rourke and Arup engineers determined that the failure mechanism was hydrogen cracking[42]. The Cheesegrater has a novel design that comprises a tapering, perimeter-braced structure with office floors connected to a support core. The structure uses over 16,000 tonnes of steel. In order to connect different aspects of the building design, 5 inch (12.7 cm) diameter steel "megabolts" are used[43].   Five of these bolts failed over a period of time. Steels with hardnesses greater than 380VHN are particularly susceptible to hydrogen embrittlement, but this can be mitigated by using appropriate "baking" procedures to drive off the hydrogen and this procedure is well-known for fasteners[44]. In order for hydrogen-induced cracking to occur it requires i) a steel susceptible to hydrogen-induced cracking ii) stress (residual or applied) and iii) atomic hydrogen to be present. A typical fracture surface on a component that has failed by a hydrogen-induced cracking mechanism is characterized by a brittle intergranular morphology. Sometimes a fracture surface will exhibit a brittle intergranular fracture around the source of the crack (e.g. a thread root) followed by a ductile fast fracture in the rest of the component that failed once a critical crack size is reached. This transition in fracture surface morphology however is not unique to hydrogen-induced cracking: it can occur from other mechanisms such as fatigue or overload. The difficulty therefore for a failure investigation is determining whether or not the initial microcrack was initiated by hydrogen-induced cracking. The main issue is determining the source of hydrogen which can either be "internal" from processes such as electroplating or "external" from processes such as corrosion.

Lough[45] notes that the presence of intergranular cracking in a material that normally fails by ductile fracture is not sufficient to confirm that a component failed from hydrogen

embrittlement (for example, temper embrittlement would also give intergranular cracking). There is no unique fracture mode that characterises hydrogen embrittlement and thus the susceptibility of the material to hydrogen embrittlement, the hydrogen content and operating environment, temperature, load, strain rate, and specimen history must all be considered. Detecting atomic hydrogen on metallic fracture surfaces is currently not possible and thus whilst it may be tempting to attribute a failure to hydrogen embrittlement, care must be taken in confirming the mechanism definitively.

Residual Stresses

Residual stresses are stresses that exist in a component in the absence of an externally applied load, that typically arise from the way in which they have been manufactured or assembled[46,47]. Two processes that particularly introduce residual stresses into components are forming operations and welding. The residual stresses that are introduced into metals from solidification processes during welding[48] can be mitigated against by performing post-weld heat treatment after welding[49]. In forensic metallurgy, examination of the microstructure or chemistry of the component alone will not show whether or not these stresses are present and other techniques such as laboratory based X-ray diffraction will be required[19,50,51]. Residual stresses in a metallic material may be beneficial (e.g. in the case of laser shock peening[52,53]) or detrimental as they can either add to in-service stresses to cause failure or provide additional load capacity and mitigate against fatigue crack initiation and growth which can enhance the operating life of a component[54]. Recent advances in design codes for aerospace materials mean that new approaches to safety from structures that contain fatigue cracks have been developed that are predicated on our ability to inspect for defects at appropriate intervals and widespread fatigue damage[55].

Design factors, Statistical Variability Issues and the Human Factor

One of the key issues for any forensic metallurgical analysis is to understand how design factors can contribute to the failure mechanisms and modes. For example, stress concentrations are known to be a significant factor in failures of structures[56,57]. Notch sensitivity is a particular issue in iron-based alloys and was an important factor in the failure of the Liberty Ships during and after World War II[58] which were also influenced by the fact the steel they were made from underwent a ductile to brittle transition at temperatures to which they were exposed during service[59]. Any metallurgical analysis of failure therefore needs to consider the impact of the particular failure modes in relation to that material.

Large engineering structures such as aeroplanes, ships, bridges and buildings are assembled from many component parts. Components may be sourced from a single manufacturer and assembled into the final product or the product may be assembled from components originating from several different suppliers. This can influence issues such as variability in mechanical properties and microstructures or variability in product size (e.g. rolled plates might be of variable thickness and microstructure[60]. Some industries operate total quality management processes with "zero defects" in order to ensure safety or give themselves the competitive edge[61].

Finally, there may be either intentional or unintentional human aspects to the failure, either by

oversight at the design stage or in subsequent inspection or repair. An example of unintentional damage was that caused to fuselage skin lap joints in aircraft by the use of sharp tools during paint and sealant removal which led to scribe marks that could cause cracks or fatigue damage[62,63].

Summary

Safety in engineering improves through our experiences of failure. Manufacturers have ever-tighter controls over metal chemistry and microstructure through heat treatment processes. Companies (particularly those working in safety-critical areas) operate stringent total quality management processes with full traceability of raw materials combined with rigorous inspection and acceptance processes. Designers have better tools and insights into effects such as stress concentration. Engineering standards for application of materials (and designs) in different sectors (e.g. nuclear, aerospace, automotive) are ever more stringent and challenging, and have built-in safety factors to try to anticipate issues; and the development and application of these standards is critically-important in preventing fatal accidents. Tools and techniques for inspecting materials before use have progressed considerably to try to engineer out unanticipated failures. However, the best design, manufacturing and assembly will never eliminate issues from human interaction with the final product. Additionally, leaner design, use of cheaper materials with less stringent standards, and new materials with as-yet unanticipated susceptibilities will keep leading to unforeseen failures. The challenge for the forensic metallurgist is in ensuring all aspects of the failure are understood from examination of the specimen history and in retrieving the relevant samples that reveal the root cause of the accident/incident or issue.

Metallurgical failure analysis is complex. There are challenges that have to be overcome, some of which are technical and others, such as financial or time constraints, that may limit the information that can be obtained during an investigation. Issues in the technical analysis of engineering failures include:

1. Can representative samples of the failure be retrieved?
2. Have the samples been properly preserved so that the fracture surface reveals information relevant to the fracture rather than issues from subsequent handling?
3. Are the analytical techniques available to the investigator that will give the necessary information?
4. Does more research need to be conducted to understand the root cause of the failure: either "pure" research to further understand a particular, novel, failure mechanism; or applied research using existing knowledge to explain the particular issue at hand.

In many legal disputes, there are often conflicting expert opinions that are tabled. For example, the report by Erichello et al.[64] showed that four different hypotheses were presented for the mechanisms of bearing failures in wind turbines. Two different bearing manufacturers identified environmental mechanisms (hydrogen-enhanced local plasticity; and brittle fracture followed by crack propagation due to corrosion fatigue cracking respectively. Two turbine manufacturers, by contrast, identified component failure (from adiabatic shear bands and severe plastic deformation, respectively. In that case that the appointment of experts with no vested interest in the outcome may have been preferable.

In the UK, for a case below a cost level of £X, the court will appoint a single expert who takes information from all parties and provides a joint report with the aim of keeping the cost down. Above this financial level, or in particularly complex cases, multiple experts will be appointed. In legal disputes, experts' reports are prepared *for the court* and each expert has to make a declaration that their report is not influenced by who pays. However, it is not always easy to demonstrate whether or not this is the case. Experts may be biased – consciously or unconsciously – by the briefing given to them by their instructing solicitor; and/or a solicitor may seek out and select and expert who is inclined towards a particular interpretation of a failure. Any investigation will also be potentially limited by financial constraints that impact on the level of analysis available and often leave the investigator in a difficult position in terms of determining the cause of the failure.

Acknowledgements

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