Diagnostic skill like that of the medical variety comes only with experience. Before experience can become of value, it is necessary to study the fundamentals be it for process control or for fault finding.
Prof. A. R. Bailey

THE INDIAN FAILURE ANALYST

A.Venugopal Reddy
Former President,
Society for Failure Analysis

Failures trigger inquisitiveness and success stimulates egoism. Egoism kills and inquisitiveness seeds appetite to learn. Learning enhances knowledge and knowledge minimizes failures.

Most of the progress made in modern technology is due to learning from failures. Thus, the importance of failure analysis as a specialized engineering discipline is growing worldwide at an envious pace.

The growing number of text books, technical papers and dedicated journals published and the numerous international conferences held in the field of failure analysis stand testimony to its ever growing relevance.

It is indeed delightful to note that India too contributed significantly to the world's knowledge base in failure analysis. But, sadly, in a country endowed with large pool of talented technical human resource, a plethora of resourceful national R&D organizations and magnificent manufacturing industries, there are only a few functional teams struggling to solve large number of production and performance related problems. The reasons for this depressing state of affairs range from our belief in *KARMA SIDDHANTAM* (whatever is destined to happen will happen) to the industry's deplorable belief that quality is cosmetic and quantity is money. Excellence in product performance and reliability can only be achieved by excellence in design, production processes, usage and maintenance. The weakness of the country in designing engineering systems is well known. Fortunately, the number of design related failures are not significant since the designs bought or copied are well proven. The incidence of failures due to abuse in extended usage and low quality maintenance too are not alarming since, as a nation, we follow directions reasonably well. However, a vast majority of the premature service failures, experience indicates, are caused by innocent abuse of science at various stages of production and more importantly, due to inadequacies in implementation of quality control procedures.

While the causes for the incidence of defects in components leading to premature failures are well documented and similar all over the world, there are certain additive factors peculiar to this country. The principal ones are (a) premature propaganda (b) ill defined production targets (c) lapses in personnel placement and (d) wide spread dishonesty. The general trend of propaganda results in producing products with immature technologies. There are many examples in the fields of defence, space and automobiles where the nation is made to expect too much only to be drowned in the despair of successive failures. Yet another important factor is the immense pressure of meeting annual production targets. The first quarter is spent in the euphoria of meeting the previous year's goals; while the major part of the production targets is realized in the last quarter. Stretching the organization to work beyond the intended limits leads to non-compliance to the stipulated standards and production of sub-standard products. There is, thus, no wonder that majority of

- **Education imparts knowledge**
- **Encouragement induces courage**
- **Endurance inculcates confidence**

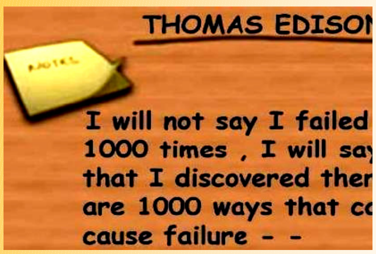
premature failure have 'last quarter product' as common factor.

Total disrespect for science is rampant in Indian engineering industry, which too contributes its might to the premature product failures. You can easily find biologists performing metallurgical functions, 'royal civils' discharging the duties of 'mighty mechs' and so on. The consequence is the lack of scientific appreciation of the causes for production problems and their ill effects on product performance. There are some industries with well-defined quality systems and there are others with no such 'fancy frills'. The quality control departments, wherever they exist, are often manned by non-performing and non-enthusiastic engineers transferred from other departments or by personnel ill qualified to handle the specialized technical tasks. Dishonesty in many forms affects the quality and reliability of products and it takes shape in all its variations with the blessings from the bosses. There are innumerable examples of the top management leaving no space for the honest to perform and the whistle blowers crying for quality being labeled as rebellious. These disturbing additive factors do contribute significantly to the incidence of premature failures. Unfortunately, most cases are made invisible through an art perfected by the management.

There are many government departments and a few major industries, which are vested with the powers to carryout in house investigations into major failures. Most often, these failure analysis experts end up taking the soft option of blaming the 'unknown factors' as reasons for failure. There are safety boards and safety regulatory authorities who carryout 'exhaustive' mandatory investigations in to major incidents involving loss of life, property and prestige under full media glare and public attention. In almost all the cases, the mandatory failure analysis boards seldom point to deficiencies in product and services but end up blaming nature (cyclones, rains, corrosion, wear and tear, visibility etc.) and human errors, only if the named ones are not alive to defend themselves. Obviously, the creators and certifiers of faulty systems cannot condemn themselves. There is therefore, an absolute and urgent need to create an independent National Accident Investigation Board (NAIB) with experts of proven ability and integrity. Such an act will surely be the most effective way to identify the real causes and impose and ensure implementation of appropriate remedial measures.

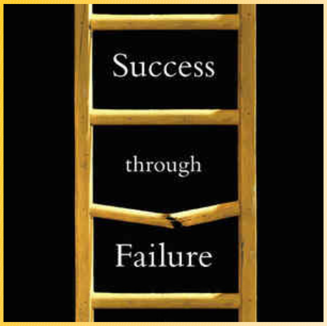
In spite of the Indian tendency to trivialize service failures, expert opinion is often sought from professional failure analysts when it is mandatory as in the case of military aircraft accidents or major disasters investigated by premier crime detectors. Fortunately, excellent failure analysis teams function in the R&D laboratories under Atomic Energy, Council of Scientific and Industrial Research, Defense Research and Development Organization and Indian Space Research Organization in addition to a few captive teams in the manufacturing sector. The services rendered by these teams are definitely laudable.

A knowledgeable few know under what constraints these teams operate in these reputed



organizations. They are always under pressure to perform to reduce the burden of backlog. Yet another undisputable fact is that while these organizations are overstaffed to the extent of incentivizing inefficiency, the failure analysis groups are grossly understaffed. The often-stated reason is that not many are willing to work in this discipline. Why should anyone choose to live under pressure-cooker atmosphere when the system permits choice! The failure analyst, unlike the rest, is under constant pressure to upgrade and broaden scientific knowledge not only in his field but also in related fields as such knowledge is mandatory to solve the mysteries of service failures. The investigator often comes under peer pressure to dilute or alter conclusions derived from evidences and experimental findings. Agreement brings stress on self-respect and disagreement is construed as disobedience. The worst disincentive to the failure analyst is the art of flawless discrimination practiced by some of the peers. If scores of confidential failure investigation reports scripted by a scientist are not treated equivalent to a technical paper published by another scientist with half a dozen coauthors, then there is definitely an unsolvable problem. Some distinguished professional bodies in the fields of science and engineering too contribute significantly in discouraging scientists from taking failure analysis as a profession. Is there one failure analyst selected for any honor by any professional society solely for his contributions to this field?

In summary, some of the principal reasons for the dwindling strength of the failure analysts flock are centered around the industry's lack of quality consciousness, the myopic and often biased attitude of the peers in science management and the lack of will to train and sustain competent failure analysts. Rich pools of experts were once developed by great visionaries like Dr. V S Arunachalam, Dr.S.R.Valluri Dr.V.Ramachandran and a few others while they were heading Indian Science and Technology Organizations. Such was the talent of these teams that many failures of national importance were solved and remedied to avoid recurrence with their expertise and leadership. However, if the present trend of neglect continues, the nation may have to soon borrow services of failure analysts from China. That will be a sad day for Indian Science. If it is accepted by the peers that lack of training encouragement and recognition are the root causes o\for the failing failure analyst in Indian, corrective measures hopefully will be in place sooner!



Smart men in the best organisations surrounded by the best datat makes the wrong decisions sometimes.

…the strongest iron will snap if over-tempered in the fire to brittleness….

PREVENTION OF FAILURES – SOME ISSUES

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On 14 April 1912, four days into its maiden voyage, shortly before midnight, the ship Titanic struck an iceberg, sinking two hours and forty minutes later. Recently, I have come across the following book: "Deadly decisions – how false knowledge sank Titanic, blew up the Shuttle and led America into War" (by C. Burns, Prometheus Books. 2002). I am excerpting below a few lines from the introductory chapter of the book related to the sinking. "There was nothing surprising about icebergs in the North Atlantic. All day Titanic received detailed information about the icebergs ahead, delivered directly to Captain Edward Smith, and to other officers on the bridge. Two hours before the incident, *Message* sent the Titanic a warning of icebergs….almost precisely where the accident later occurred. At least one report was given to Bruce Ismay, President of the White Star Liner. Eager to set a new record for transatlantic crossing, Ismay calmly stuffed the note in the pocket. Ismay believed three things to be true: First he knew from his own experience…that the lookout would give him actual sightings of any iceberg in time to steer around it. Second, his team of engineers assured him that even if the Titanic struck an iceberg submerged or otherwise difficult to see, the ship would not sink. And third, if there should be an accident of any kind, there was tight and mutually supportive community of ships nearby that would come to his aid. He was wrong on all counts…Smart men in the best organizations surrounded by data make the wrong decision…." Reading these lines, I remembered the blowing up of Air India Plane Kanishka on 23 June, 1985 in mid-air (at an altitude of 31,000 feet) by a bomb in Irish airspace, crashing into the Atlantic Ocean. Could this disaster have been prevented? I had an opportunity to listen to a talk given by Dr. V. Ramachandran (of National Aerospace Laboratories, Bangalore) based on his experience as the chief failure analyst deputed from the Indian side to analyse the cause of the blowing up of the aircraft. Though naturally, Dr. Ramachandran could not divulge all the results that the analysis brought out, it was clear from his presentation that the analysis was able to establish that the blowing-up had been the result of the detonation of a bomb. *(Though it was not told by Dr. Ramachandran, some of us came to know later that deformation twin had been observed in the microstructure of samples taken from the body of the aircraft. Deformation twin is rare in the microstructure of a fcc aluminium alloy – unless perhaps there is a shock loading)*

Any failure analyst, after carrying out an analysis and giving his recommendations to the client, would always think – could the failure be prevented? The problem is, a failure analysis may correctly conclude on a contributory cause of failure – such as wrong materials choice, inadequate fabrication, overloading etc. But in most of the cases, he is not in a position to zero in the root cause.

In analysis of failures, understanding the chain of events is important.

For example, who was responsible for the wrong choice, and why he made the choice. May be the decision was taken by a person who was not supposed to take the decision. And even if he was, he might not have been well qualified or trained to take such decisions. The diagnosis of the failure analyst then gives the management ideas as to how, in foolproof manners, the various stages of life cycle of a component be managed.

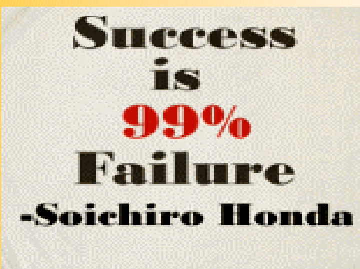
CAUSE AND EFFECT

After many years of experience in failure analysis of engineering materials and components, I can now better perceive an important philosophical term **"Causality**". Simply put, Causality is the relationship between an event (the *cause*) and a second event (the *effect*), where the second event is a consequence of the first. As Aristotle wrote, all causes are beginnings. We have scientific knowledge when we know the cause and to know a thing's nature is to know the reason why it is. Aristotle marked two modes of causation: proper (prior) causation and accidental (chance) causation. In logic, causes are often distinguished into two types: Necessary and sufficient. A third type of causation, which requires neither necessity nor sufficiency in and of itself, but which contributes to the effect, is called a "contributory cause. If *x* is a necessary cause of *y*, then the presence of *y* necessarily implies the presence of *x*. The presence of *x*, however, does not imply that *y* will occur. If *x* is a sufficient cause of *y*, then the presence of *x* necessarily implies the presence of *y*. However, another cause *z* may alternatively cause *y*. Thus the presence of *y* does not imply the presence of *x*. In the case of contributory cause, the presumed cause precedes the effect, and altering the cause alters the effect. It does not require that all those subjects which possess the contributory cause experience the effect. It does not require that all those subjects which are free of the contributory cause be free of the effect. In other words, a contributory cause may be neither necessary nor sufficient but it must be contributory. If we carefully think, we can see examples of failures under all the situations mentioned above.

Cause and effect relationships are dealt with in many areas – in Physics, biology, medicine, economics, and engineering for example. Of course, it is also dealt with – consciously or unconsciously – in failure analysis. Consideration of cause and effect relationship is inherent in fault tree analysis, root cause analysis, and risk analysis.

WHY DO WE CARRY OUT FAILURE ANALYSIS?

While it is true that failures are the pillars of success, if we no not know why and how the failure took place, we cannot translate the failure into success. In the present day advanced scenario, we do have possibilities of simulation, modeling etc, but a database created based on experience and correct failure analysis, and using the same can go a long way in designing a system whose probability of going wrong in practice is low. It is certain that man, through all the ages, have observed failures and used their analysis later to prevent failures. An example is given from the Greek Play "Antigone" written by the famous 5th Century (BC) writer Sophocles.



In one place, Creon is describing the nature of "Antigone" as follows: "...Ah, but you will see. The over-obstinate spirit is soonest broken; as **the strongest iron will snap if over-tempered in the fire to brittleness**. A little halter is enough to break the wildest horse...." The ancient Egyptians knew the strength and resilience of of a layered structure like plywood. Well it may be true that we now know many of the intricate details of materials properties because of the availability of a wide range of characterization techniques, supported by advancement of science & technology, but the analysis and thought process as to how to prevent the failures have been a characteristic trait of the humans since they switched over from being gatherers to hunters.

SCIENCE TO THE AID OF FAILURE PREVENTION

In the medieval period, often the wood structure of ships would be covered by copper strips. The strips would be put in place by iron nails. Soon it was found that the iron nails got corroded quickly in seawater. Nobody could figure out why – till Faraday and Davy "came into the picture" in the early part of the nineteenth century. We now knew the electrochemical cause of corrosion and also how to prevent the iron nail corrosion by using sacrificial electrodes made up of zinc. This relationship of the scientific knowledge and failure prevention is necessarily continuing and would continue. The real challenge will however come, when nano-technology will become widespread.

PARTING REMARKS

In analysis of failures, understanding the chain of events is important. The essence of the following nursery rhyme which all of us learnt when we were kids is strikingly pertinent for failure analysis. *For want of a nail the shoe was lost // For want of a shoe the horse was lost // For want of a horse the rider was lost // For want of a rider the battle was lost // For want of a battle the kingdom was lost // And all for the want of a horseshoe nail. *Well, if the nail failed, the moot question is why and how the nail failed. Was it a proper (prior) causation or an accidental (chance) causation? What is the root cause of the failure of the nail in the first place?*

There are situations wherein the investigator faces dilemma in drawing conclusions from the microstructural evaluation alone unless a history of similar failures can be established.

Engineering Failure Analysis: *Microstructural Evaluation and Interpretation*

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Microstructural examination provides the failure analyst a good indication of the class of material involved and its structure. The microstructure has strong influence on the properties of the material and their behaviour during service. Frequently, this examination can pinpoint errors made at various stages of the component fabrication such as processing, heat treatment, surface treatments, casting, welding etc. Service effects such as corrosion, oxidation and microstructural degradation are also revealed, and their extent can be investigated. Microstructural study is, therefore, helpful in confirming the probable cause of failure and elimination of other possibilities. Hence, it should be conducted as a routine procedure wherever possible. But, interpretation of the observed microstructures with relation to the failure causes is not always straightforward. There are situations wherein the

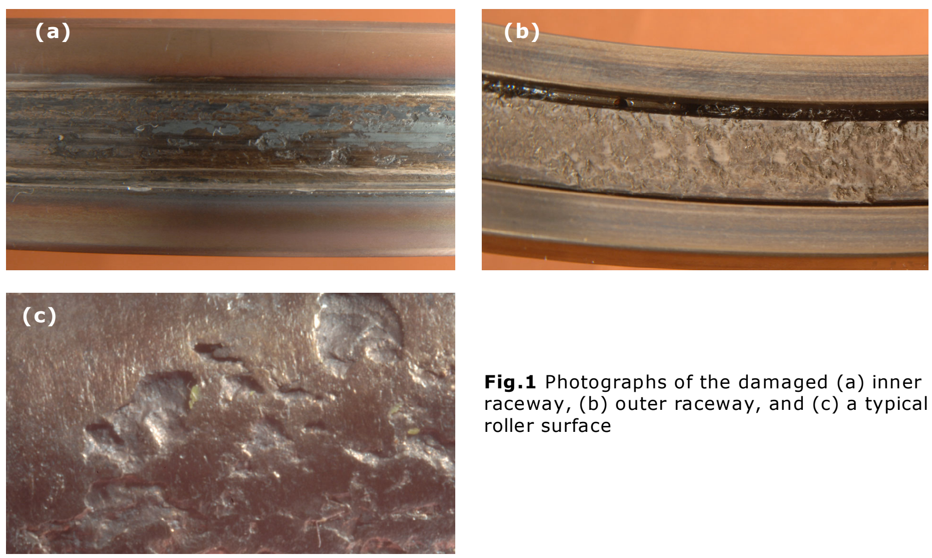


Fig.1 Photographs of the damaged (a) inner raceway, (b) outer raceway, and (c) a typical roller surface

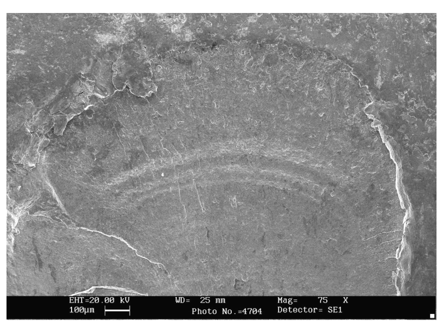


Fig.2 Scanning electron photograph showing beach marks on the spalled surface, typical of fatigue crack propagation

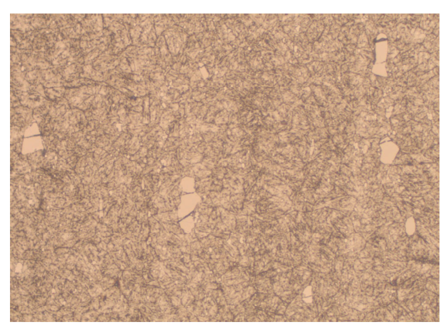
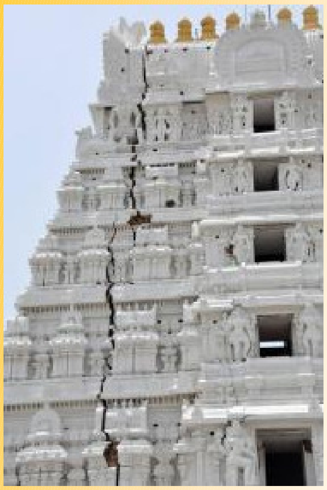


Fig.3 Optical microstructure of the roller material consisting of tempered martensitic matrix dispersed with carbide particles

500-yr-old temple tower collapses in Andhra Pradesh!



The structure had been developing cracks for over a decade. Temple authorities brought this to the government's notice several times. Experts from IIT-Chennai warned that a strong wind was enough to bring down the dilapidated structure- *The Hindu, 28th May 2010*

investigator faces dilemma in drawing conclusions from the microstructural evaluation alone unless a history of similar failures can be established. Yet, circumstances sometimes dictate that conclusions be drawn with the limited data available. In this article, I share the experience of such an investigation.

In recent past, I was investigating a recurring failure of roller bearings of a particular type of aero engine. The bearings were made of a martensitic steel similar to M2 grade tool steel, and they were intended for application in an environment with maximum temperature of 400^0C. The total technical life of the bearings as per the designer was 1000 hr. It was reported that in a few cases, the failures in the bearings occurred in service lives of 350-850 hr range.

The bearing that was submitted for investigation to our laboratory had logged in about 850 hr at the time of failure. The bearing had severe post failure secondary damages. All the bearing elements were discoloued due to heat effects. Flaking, spalling and flow of material on the rolling surfaces were widespread (refer Fig.1). There was transfer of material from one surface to another by adhesive wear mechanism. This had resulted in plucking-off of material from the rolling surfaces leaving behind craters.

Although most of the failure signatures were obliterated due to secondary damages, evidences of primary mechanism of failure were still preserved on some of the rollers. Through scanning electron microscopic study, it could be established that the failure of the rolling elements was by surface contact fatigue (refer Fig.2). This study was followed by detailed material evaluation including microstructural examination.

The material of the bearing elements was found to conform to specification with regard to chemical composition, cleanliness of the steel, inclusion rating and hardness. The microstructures of all bearing elements were similar and they consisted of tempered martensitic structure dispersed with carbide particles (refer Fig.3). There were two types of carbides in the structure; one rich in tungsten and the other rich in vanadium. Vanadium-rich carbides were relatively larger in size compared to those of the tungsten-rich carbides. By and large, the microstructure was found to be acceptable for the specific grade of steel that was used. However, the only abnormality that was noticed

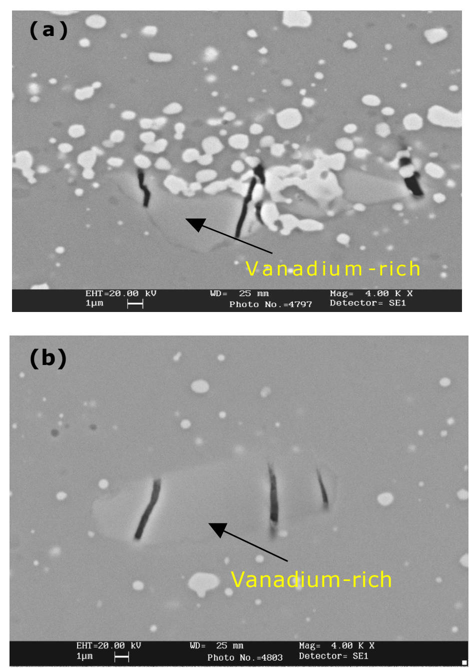


Fig. 4 Scanning electron micrographs showing cracks in the vanadium-rich carbide phase of rollers: (a) failed bearing, and (b) unused bearing

An investigation grounded in sound scientific data can ascertain the mode and root cause of component failure with minimal time and money.

http://www.rdmag.com/Featuredarticles/2010/02/Materials-Materials-Testing-The-Failure-Analysis-Puzzle/

during this study was in the microstructure of the rollers, wherein most of the vanadium-rich carbide particles showed presence of parallel cracks (refer Fig.4a). At this point of time, it was a significant discovery. It was thought that these cracks in the microstructure could have serious effect on the performance of the bearing because of the following reasons.
The cracks present in the microstructure are defects and they are likely to propagate progressively under the repetitive load during service. In case of rolling element bearing, the vulnerable crack propagation zone being at the subsurface, where the maximum shear stress exists, surface contact fatigue failure in rollers can, therefore, be more predominant in the presence of these defects. Also, the cracked carbide particles can get dislodged from the surface, which subsequently, can act as abrasive particles leading to rapid deterioration in the rolling surfaces. The increased friction resulting from this, can again promote surface contact fatigue on the rolling surfaces. Although the above microstructural analysis for a possible surface contact fatigue failure in the rolling elements was quite convincing, it proved to be extremely difficult to establish the origin of the cracks in the vanadium-rich carbide phase, that is, whether they were present in the starting material itself or they got developed in service. Moreover, the presence of cracks only in the microstructure of the rollers and not in the races added additional complexity to the problem.

I was apprehensive of reporting this analysis without being certain about the role of microstructure on the failure in hand. Failing to get any information on this issue from the manufacturer of the bearing, I had to fall upon conducting a comparative study. For this purpose, rollers were chosen from an unused bearing as well as a life expired bearing that had successfully logged in 1000 hr in one of the engines. The results of this study confirmed that irrespective of whether or not the bearing was in service, cracks were present in the vanadium-rich carbides of all the rollers (refer Fig.4b). This exercise was helpful in establishing unambiguously that the cracks in the carbide phase were present in the material of the rollers to start with, and they did not get developed during service. This was again a significant discovery, and it put to rest all speculations on the role of microstructure on the failure in question. It was apparent from the study that the contributory factors for the recurring premature failure of the bearings were some issues other than the microstructural aspects. Hence, in this case, further investigation into determination of the origin of cracks in the carbide phase of the rollers became inconsequential. Nevertheless, it was important for the manufacturer to look into this aspect and eliminate these microstructural defects for a possible enhancement in the performance of the bearings, in general.
It emerged from the laboratory study that the primary cause for surface contact fatigue failure of the bearing was yet to be established and hence, the investigation needed to continue further. It was a difficult task to strike a balance between the microstructural analysis and the final recommendations in the

report. It appeared that emphasis on the microstructural observations in isolation could misdirect the investigating team with a risk of missing the important failure causes. Anticipating the possible turn of events that could take place, I thought that these ethical concerns were of utmost importance at this stage of investigation rather than stressing upon finer microstructural details. Hence, I chose to maintain silence on the microstructural issue, and recommended for a system level investigation. I was convinced that the observed microstructural abnormality was not the cause of failure in this case.

Ignorance leads to ignoring well-known facts

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Failure analysis and prevention are important functions to all of the engineering disciplines. The materials engineer plays an important role in the analysis of failures, whether a component or product fails in service or if failure occurs in manufacturing or during production processing. In any case, one must determine the cause of failure to prevent future occurrence, and/or to improve the performance of the device, component or structure.

Failure can occur due to improper choice of material or improper processing parameters or operation errors or adverse effects of service environment (Fig.1). If the factors to the primary cause of failure are known or understood, it is essential for the designers and material specialists to take note of the suggestion so that repeated failures do not occur. However, it is not always the case as many known failure modes are ignored when designing components discussed over the following failure cases.

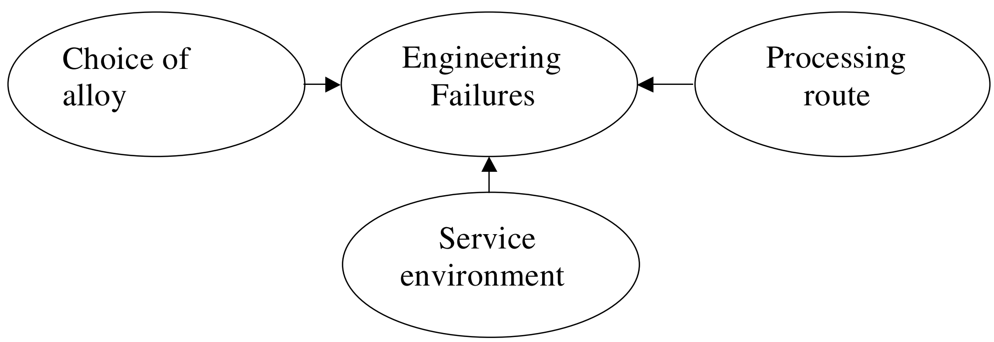


Fig. 1. Schematic describing the causes of engineering failures

It is well known that the choice of 304 stainless steel for a service temperature of ~480º C is prone to cause sensitization. A premature failure of 304 SS flange in a welded joint with 316 SS pipe serving in sodium environment was reported due to caustic embrittlement. Choosing 304 SS was found to be the primary cause for the failure as the material was profoundly sensitized as can be observed in Fig.2.

Choice of parameters for processing is an important factor in determining the component attaining necessary strength and sustains the service degradation till its lifetime. Heat treatment of components is an important aspect to introduce necessary surface properties, strength and overall toughness. Wire ropes employed in service of coal handling were reported to fail within its life period due to unexpected surface degradation which was found to be due to decarburisation effect caused by the heat treatment. If the temperature and partial pressure of the furnace environment were controlled properly, the decarburisation effect on the surface would have been avoided

New Dimension to Failure Analysis, Using XRF Technology

In general, X-ray fluorescence spectrometer (XRF) has been in use for many years in the analysis of chemical composition.

The methods employed have consistently advanced in the same stride as the instrument technology itself. Today, XRF analysis is a reliable method of predicting the onset of abnormal wear or resolving failure analysis issues in hydraulic systems.

www.machinerylubrication.com/Read/249/xrf-failure-analysis

A failure is a failure of imagination!

(Fig.3).

A wire rope of a tower crane used in a construction site suddenly failed while lifting a bucket containing a load. It was observed that the wire rope employed does not meet the recommended specification of construction, viz. capable of rotation during service. This resulted in the rope not meeting the demand of the service conditions where rotation of the wire while lifting the loads was quite common. As a consequence, the wire was subjected to friction heating each time it passed around the swivel. Consequent microstructural degradation led to soft surface layers and found responsible for the final failure (Fig.4).

Summarising, it is quite often observed that the ignorance exercised in choosing the right material or right parameters during processing or right construction method to meet service environment was found to cause failures. The above experiences clearly indicate ignorance leads to ignoring otherwise well-known problems and makes one wonder that a failure is a failure of imagination!

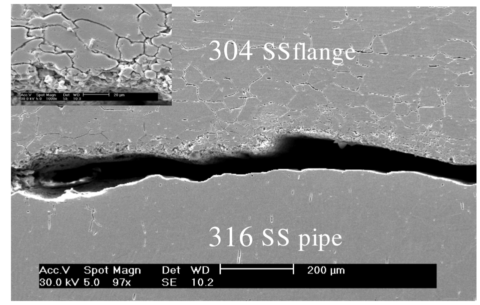
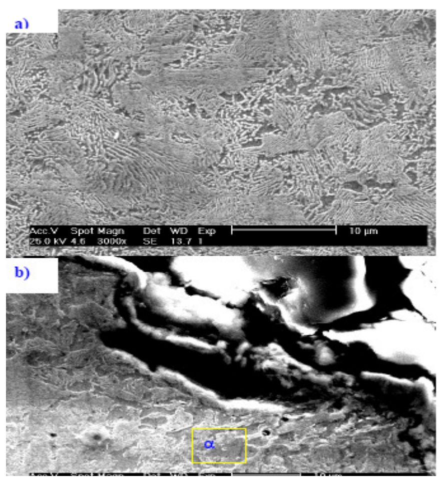


Fig.2. Sensitized 304 SS flange (top left inset); below, unsensitized 316 SS pipe



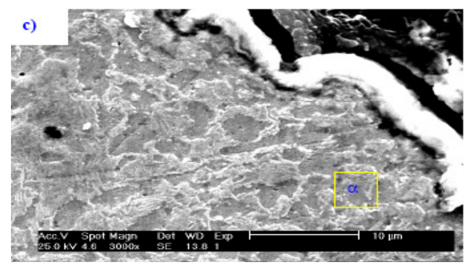


Fig.3.(a) core of the wire is pearlitic; (b)Edges with cracks showing ferrite+ pearlite; (c) in detail (b); note Ni layer intentionally made for preserving edge (white deposit)

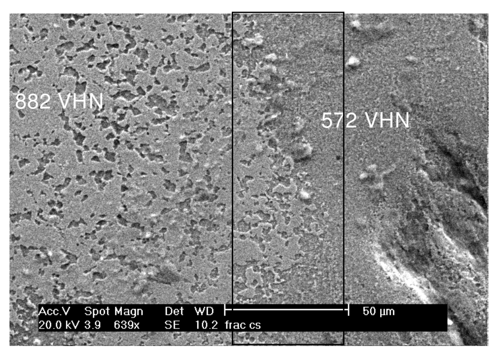


Fig.4. Cross Section Close to the failed region shows decarburised area indicated by a rectangle

Thomas Edison failed approximately 10,000 times while he was working on the light bulb.

Henry Ford was broke at the age of 40.

Henry Ford II fired Lee Iacocca at the age of 54.

Young Beethoven was told that he had no talent for music, but he gave some of the best music to the world.

All success stories are stories of great failures.

Root Cause Analysis of Fatigue Failures of Compressor Blades of Aeroengines

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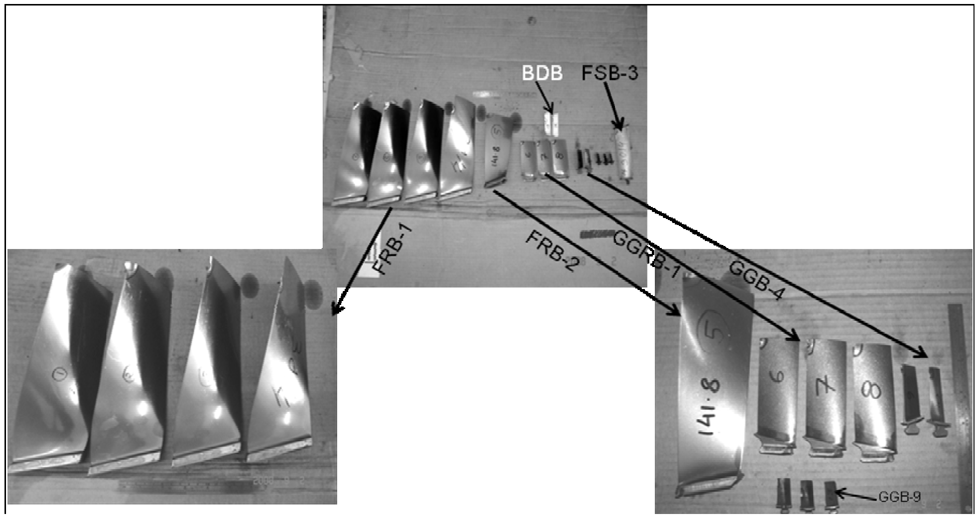
Foreign object damage (FOD) is responsible for majority of failures of compressor blades of aeroengines worldwide. FOD is usually considered to be caused by soft/hard large objects. However in recent times, sandy and marine environments in coastal regions have caused sand abrasion induced failures of compressor blades. Therefore, for all practical purposes the sand induced abrasion of compressor blade may also be considered as FOD. Usual FOD appeared as nicks, dent, cut marks of various forms on the airfoil which in turn, reduces the fatigue strength of the material. FOD can lead to severe reductions of expected high-cycle fatigue (HCF) life. This reduction in fatigue life due to FOD is associated with four main factors: (i) impact-induced residual stresses, (ii) microcracks formed upon impact, (iii) the stress-concentrating effects of the impact site, and (iv) distortion of the microstructure. The prediction of the fatigue behaviour is extremely difficult because of the many factors that may contribute to the overall behaviour. LCF involves early crack initiation and a long propagation life as a fraction of total life. LCF cracks are typically of inspectable size. HCF on the other hand requires a relatively large fraction of life for initiation to an inspectable size. This results in a very small fraction of life remaining for propagation. Therefore, metallurgical investigation of FOD to compressor blades is always necessary to confirm that it is FOD and not metallurgical defect that is responsible for the fatigue failure. The following cases presented below illustrate the various types of FOD induced material degradation that has resulted in fatigue failure of blades. Consequences of FOD can have serious flight safety implications.

1. FOD Damages to Compressor Blades of Mig-29 aircraft

The damages appeared as tear/shear, nicks, dent at leading edge of 1st to 9th stage blades. Intensity of damage decreases with increasing stage number. Investigation at FOD impact site indicated the presence of impregnated traces of rock having combination of different mineral phases of varying stoichiometry. However, the 8th stage gas generator blade, which is made of steel, is impacted by rock & Ti-alloy (fractured pieces from blades of forward stages). The variation in damage intensity in successive stages indicated that the foreign object projectile followed path of reducing radius in between the successive collisions.

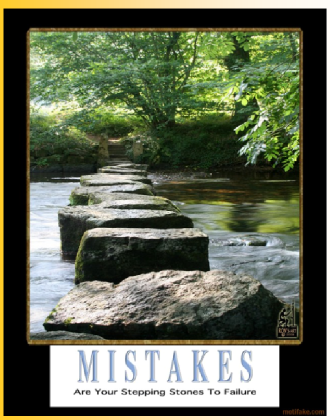
2. FOD Dent/Abrasion/Corrosion: 1st Stage Compressor Blade of R-13-300 Aeroengine

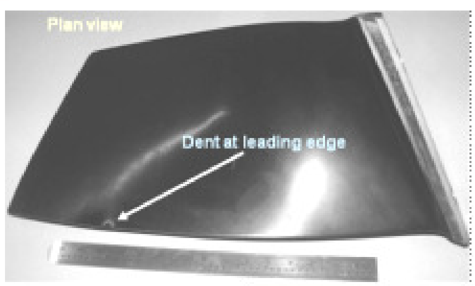
The first stage compressor rotor blades are made of enamel coated steel. Dent close to leading edge and complete erosion of enamel layer at leading edge are observed. XRD residual



stress analysis revealed reduction of beneficial compressive residual stress in neighbourhood of the dent. This may lead to reduction in fatigue endurance strength & number of cycles to failure. Moreover, erosion at leading edge of the airfoil is unavoidable in operating conditions/area. This resulted in pitting corrosion, which may initiate fatigue failure of blades, if it is not detected before the onset of fatigue crack initiation.

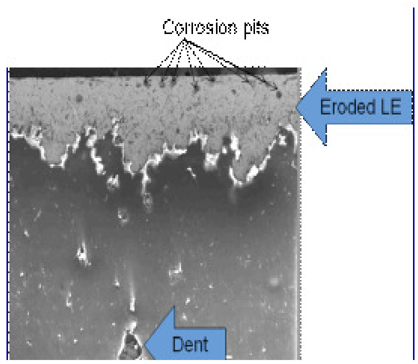
Recommended shorter inspection interval of leading edge to determine the starting time of coating erosion.





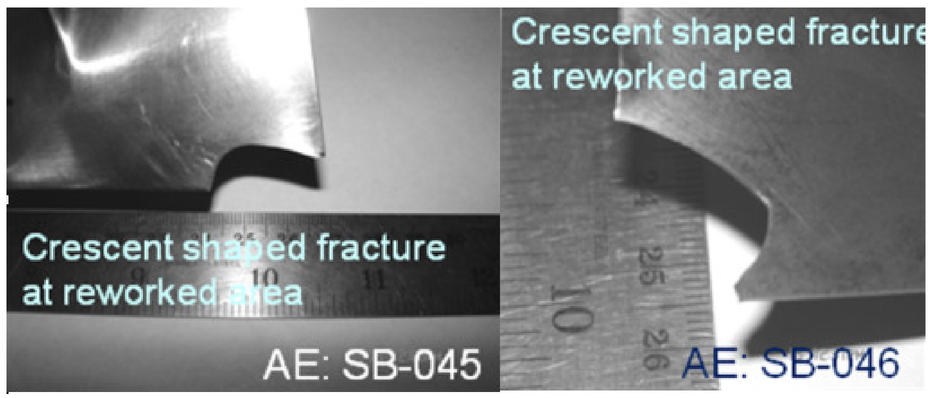
XRD Residual Stress Around Dent

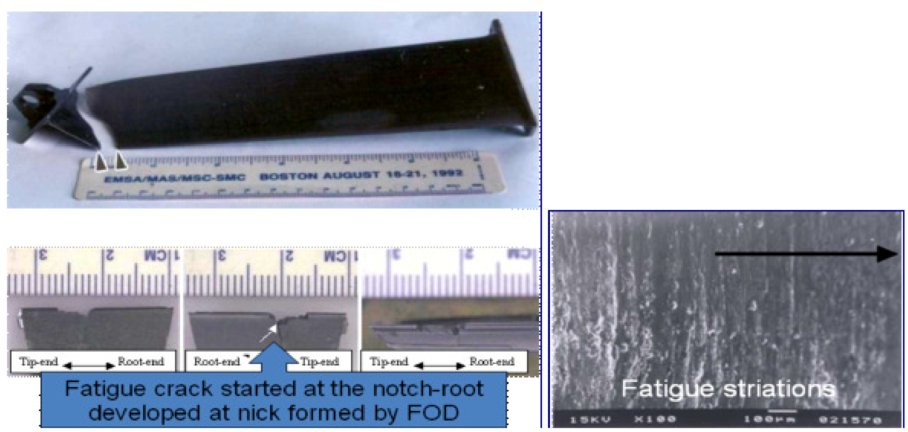
Locations	Concave face (Pressure)	Convex face (Suction)
Mid Airfoil	-376.1 MPa	-444.0 MPa
1	-325.6 MPa	-255.3 MPa
2	-206.0 MPa	-270.3 MPa
3	-200.1 MPa	-127.2 MPa
4	-21.8 MPa	-74.0 MPa



3. Reworking Induced Fatigue Fracture of 1st Stage Compressor Blades: AL-31FP Aeroengines

As per OEM's procedures, the dented compressor blades are reworked manually to desired profile, only if the dent size is within the permissible limits. These blades are made BT3-1 (α-β titanium alloy), operated at 13500 rpm with axial pressure 1kg/cm^2, and used for less than 550 hours. Investigation revealed the fatigue failure at reworked locations which is imprinted with scratches due reworking. Thinning of edges due to reworking is also observed. The reworking by hand grinding generated; (a) wear grooves, (b) reduced blade thickness, and (c) tensile residual stress. The



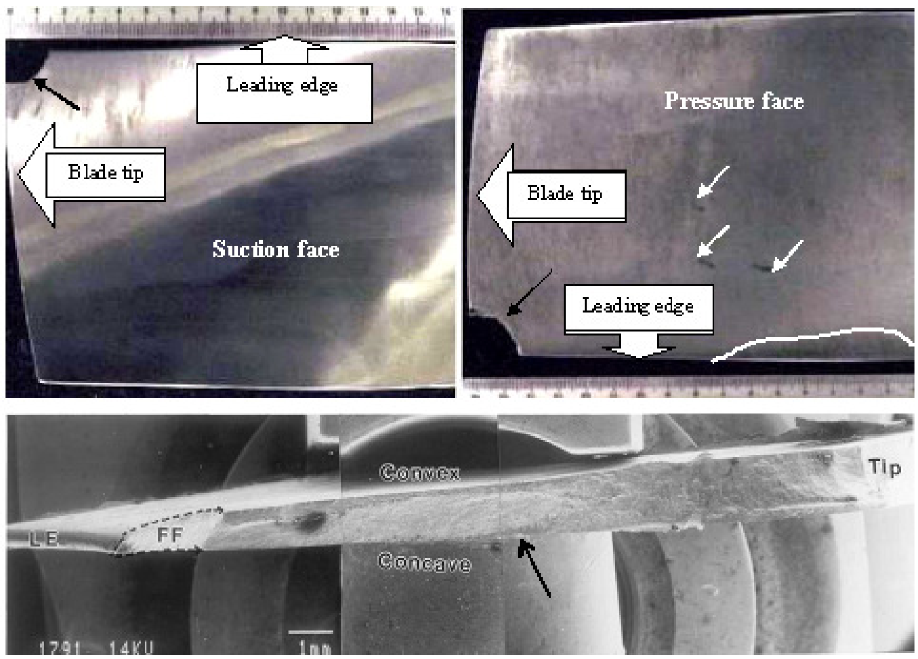


fracture of reworked blade portion is due to fatigue mechanism. The scratches due to reworking act as stress concentration sites while other two factors assist fatigue crack initiation at reworked location.

Recommendations: To develop a methodology of reworking of the nicked/dented blade with improved surface finish, less reduction in blade profile/thickness and elimination of tensile residual stress generated during reworking.

4. FOD/Nick Induced Fatigue Failure of 2nd Stage Stator Blade of Aeroengine

In this case FOD generated a nick of 6 mm length & 1.5 mm depth at leading edge on a second stage stator blade made of BT3-1($\alpha+\beta$ Titanium alloy). The depth of nick is beyond the acceptable limit of permissible depth of 0.7 mm. Service exposure of the blade is 697:31 hrs & time between overhaul is 550 hrs. Therefore, nick formed during last 147:31 hrs of operation by FOD. Investigation revealed that the fatigue crack started at the notch-root developed at nick formed by FOD.



FAILURES DUE TO HYDROGEN EMBRITTLEMENT

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Hydrogen embrittles several metals and alloys and the defects can range from a slight decrease in the percentage of reduction of area at fracture to a brittle macroscopic fracture at a relatively low applied stress. Even small ppm of hydrogen can have a deleterious effect, particularly for high strength steels, causing hairline cracking. Even when the quantity of gas in solution is too small to reduce tension test ductility, hydrogen induced delayed fracture may occur.

Hydrogen is absorbed from the environment followed by diffusion to regions of high tensile stress particularly areas with notches. Hydrogen pickup from manufacturing either during pickling or plating can be one of the main causes of hydrogen embrittlement. Plating solutions and plating conditions selected to produce high cathode efficiency minimize the amount of hydrogen generated on the metal surface. Metal coatings often prevent the hydrogen from leaving the base metal. Elevated temperature baking after plating is generally required to allow the hydrogen to move to micro structural positions in the part interior that are less damaging to the atomic bonds. One such case has been discussed here.

PART I- H_2 from plating

Fork end of a Frame attached with a tie rod has failed suddenly in a brittle manner. The failed fork end and part of the tie rod assembly is shown in Fig. 1a. Fig. 1b shows the failed portion of the tie rod. It is seen from Fig. 1b that failure has occurred inside the tie rod from a thread on the fork end. Fracture surface shows bright features and cracks emanating from the thread groove and also cracks on the surface of the thread as seen in Fig. 1c. The Fork end of the frame and the thread portion were found to have a golden yellow coating.

SEM fractographs of the initiation region has shown cleavage fractures as shown in Fig. 2. Away from the fracture and most of the failed regions also have shown cleavage features. The coating analysis of the fork end revealed it to be Cadmium on the

Fig. 1a Photograph showing as received condition of broken fork end and tie rod of frame.

Fig. 1b Magnified view of the broken tie rod showing dent mark and bright fracture surface

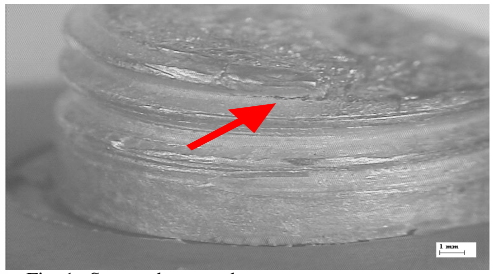

Fig. 1c Stereo photographs showi ng cracks near the thread root and on the surface of the thread in the fork end.

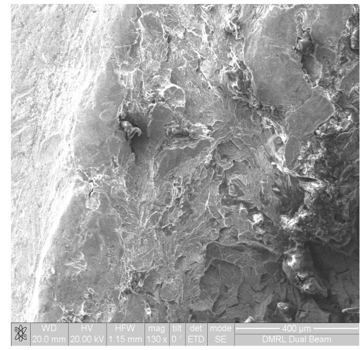

Fig. 2 SEM fractograph of initiation of cleavage

surface. Upon etching with 2% nital solution the microstructure appears to have pearlite and ferrite and a network of grain boundary ferrite (Fig. 3). The Vickers Hardness of the threaded shank of the fork end at 10 Kg load is found to be $280HV_{10.}$

The chemical composition of the material suggests that the fork end of the frame might have been manufactured from steel nearly equivalent to AISI 1050 steel grade. The microstructure and hardness shows that the material has been used in normalized condition. The elliptical nature of the inner diameter of the tie rod indicates that the tie rod has undergone severe deformation may be by impact bending loads. A dent mark on the surface substantiates this.

The cleavage fracture throughout the fracture surface is indicative of brittle fracture and suggestive of embrittlement. This type of failure by cleavage fracture in a cadmium-coated sample could be due to hydrogen embrittlement. Presence of cracks at other thread regions also suggests that hydrogen embrittlement could be the reason for the failure. Hydrogen embrittlement occurs when proper baking after cadmium coating has not been carried out. In the present case the failure of the fork could have been initiated by Hydrogen embrittlement and catastrophic failure has occurred may be due

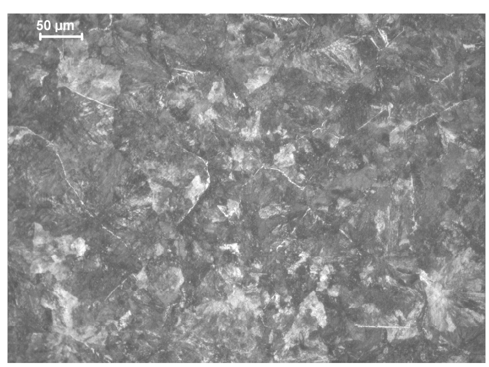

Fig. 3. Photomicrographs of the failed shank showing ferrite and pearlite.

PART II Hydrogen in welds

The presence of hydrogen in a weld is generally due to moisture that is introduced in shielding gas. A case study has been presented here to show how hydrogen present in environment can cause failure in an important pressure piping.

A pressure pipe manufactured using Maraging steel has failed at weld location during pressure testing at 95% of proof pressure. Acoustic indications have been noticed at 85% of proof pressure levels. However, the testing could not be stopped as the acoustic indications are not continuous and were observed as bursts. Visual examination revealed that the failure has occurred along the circumferential weld joint. A flat fracture region to an extent of approximately 400 mm on one side and 150 mm on the other side of the L – seam along the circular seam was observed. The remaining fracture area shows a zig-zag pattern for the crack path. However, most of the path the crack has travelled in the weldment i.e. weld region and heat affected zone (HAZ) and not in the parent metal or L-seam. Fig 1 shows a part of the flat fractured region revealing chevron pattern indicating the crack propagation direction. Tracing the chevron pattern in the opposite direction to crack propagation, leads to the probable crack initiation region. It is seen that these chevron markings point out to a valley or step. It is also seen that the other side of this feature chevron markings are moving on the opposite direction indicating that this region could be the initiation region. It is to be noticed that the fracture features (Fig. 1) up to two thirds of the thickness of the material shows cleavage pattern while the remaining area shows slanted fracture with flat features. Fig.1 also shows the area corresponding to the opposite part showing the protrusions of material at probable crack initiation region.

The region suspected to be the initiation region shows bright fracture to nearly two third of the thickness of the plate while the remaining one third has dull or gray fracture features. The SEM images (Fig. 2a, b, c) show separation between the root pass weld and first pass weld regions. The fracture features in the first pass weld region show cleavage features and secondary cracking (Fig. 2d, e, f) while root pass showed slanted fracture with smooth features. The region containing bright fracture features mostly shows cleavage and intergranular features at some locations (Fig. 2d, e, f).

Optical Metallographic examination carried out revealed (Fig. 3) that the weld on the top region shows overlap of weld bead and the visible bead width is around 8-9 mm which is generally longer compared to normal weld indicating that this could be the weld repair zone. The figure also shows HAZ and parent metal regions. It can also be noted from Fig. 3a that weld bead appears to be separated from the V groove. The weld and parent metal microstructure appears to be normal and contains fine voids consisting of fine white particles and microporosity (Fig. 3b).

The chemical analysis of the parent metal confirmed that the pressure piping has been manufactured from maraging 250 grade steel. The chemical analysis of weldment at the initiation region and remaining fractured region in the weld matches with that of W2 filler, which clearly indicates that there was no mix up of filler wire. The microstructure of the parent metal, weldment and HAZ at and away from the initiation region revealed that the material is used in aged condition. However, at the initiation region close to the parent metal and weld interface fine voids associated with white particles, which may be reverted austenite, were observed. The separation of the weld bead and parent metal was also seen at the V groove which suggests that proper precautions have not been taken during welding. The separation generally occurs when there is a fine oxide layer developed at the interfaces. The fracture initiation zones were found to be 125-170 mm on both sides of the L-seam along the circular seam. Discussion with users and manufacturers revealed that weld repairs were carried out in these two zones. It is to be noted that in these regions where initiation of failure has taken place, there is separation of root pass and first pass and brittle cleavage fracture initiated at this interface.

The cleavage fracture and the intergranular fracture observed at the initiation region are indicative of material embrittlement. The embrittlement in maraging steel may result from the following.

1. Sub zero impact conditions.
2. Stress Corrosion Cracking (SCC).
3. Hydrogen Embrittlement.

In this case, the failure under sub zero impact conditions is ruled out as the temperatures at the time of pressure testing are ambient temperatures i.e. around 22°C - 30°C. In this temperature range, even under impact conditions maraging steel fails under ductile dimpled mode. Furthermore, it is to be noticed that the pressure testing has been carried out under quasi-static conditions. In view of this and based on the evidences of fracture the failure in this present case is not due to sub zero treatment.

The fracture surfaces do not contain any corrosion debris. It can also be seen that the cleavage has initiated from root pass and first pass interface and not from any of the surfaces. This clearly indicated that the initiation of failure is not because of stress corrosion cracking (SCC).

The porosity observed in the weldment and association of reverted austenite with some of these voids indicates entrapment of gasses which could be hydrogen. The cleavage and intergranular fracture features and gaseous porosity observed in the microstructure points out to the embrittlement due to gasses and may be because of hydrogen. Based on the evidences it may be concluded that the failure of maraging steel pressure piping in the weld was initiated by hydrogen embrittlement. Hydrogen embrittlement could be due to

1. Excessive humidity in the surroundings during welding.
2. Excessive presence of hydrogen in the filler
3. Hydrogen pick up prior to and during welding.

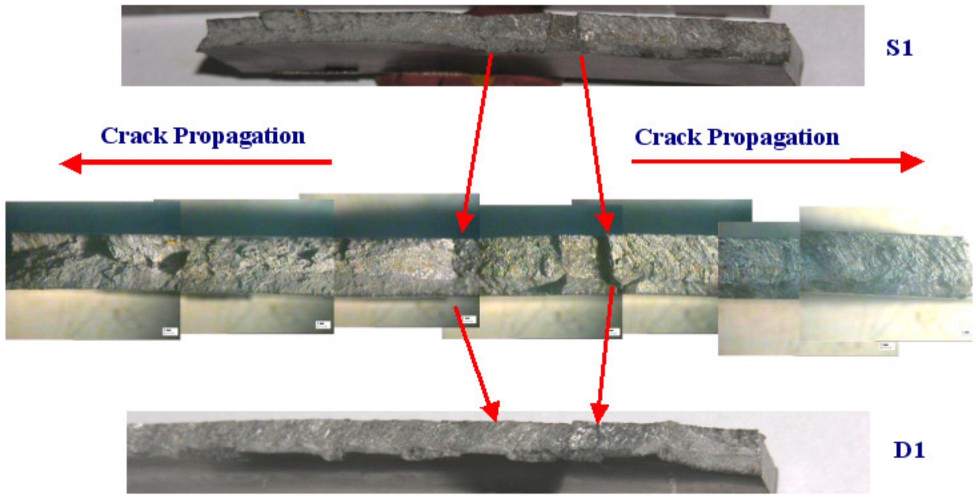

Fig. 1 Images showing chevron pattern indicating the fracture initiation site

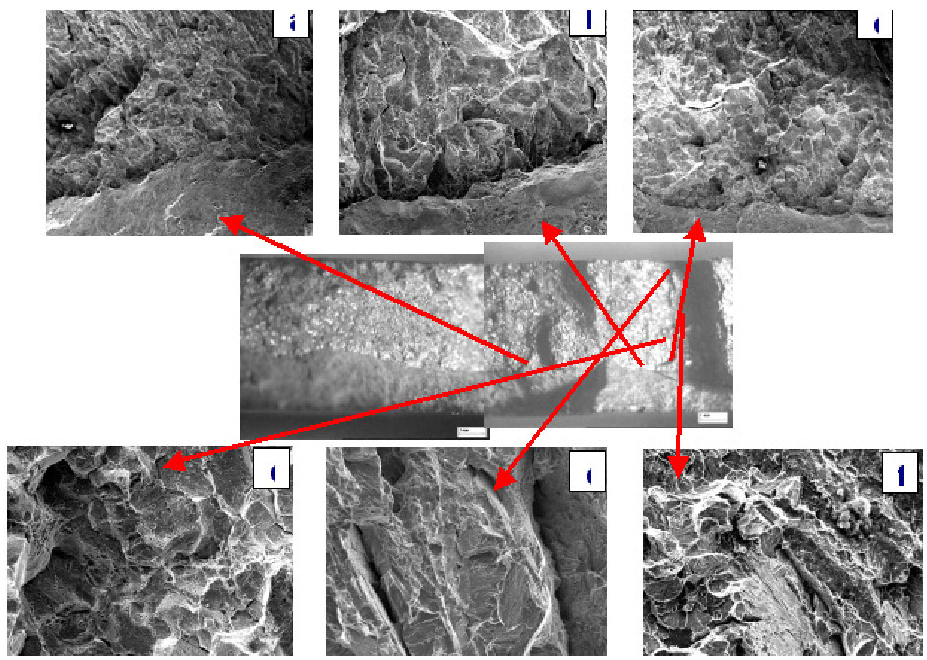

Fig. 2 SEM images of fracture surface showing cleavage and intergranular features

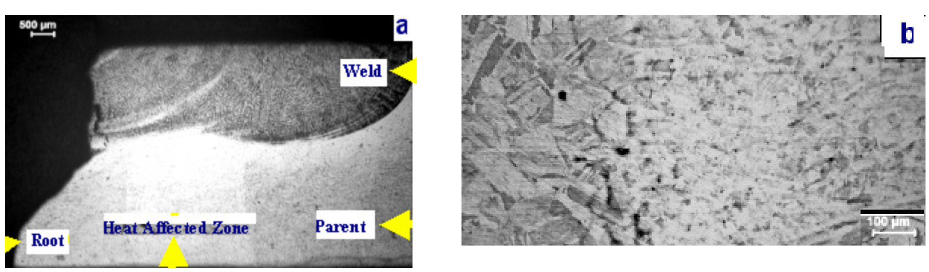

Fig. 3 Images showing (a) weld bead separation
(b) weld and parent metal interface showing microporosity.