Failure analysis – a duty of IPT

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Abstract

Since the early 1900's, the time when IPT acquired its first optical microscope for metallography, failure analysis has been an important activity which IPT has always been involved in. The term failure analysis has a broad meaning, but the intent now is to restrict this meaning to the analyses performed on fractured or cracked mechanical components and structures intended to determine their causes. Cases related to loss of stability of structures due to deformation, wear and general corrosion, which are also considered failures, will not be treated in this article. Engineers normally try to design machines, engines, and all sorts of mechanical components and structures to be failure proof. For that material selection, manufacturing processes, assembling, and maintenance recommendations are carefully specified. The obedience to these specifications normally prevents failures. However, if one or more of the items specified above is not obeyed, the possibility of failure will increase. Furthermore, there are situations, in which even though all the specifications are followed by the book, a part can fail, and an accident ensues. Some selected failure analysis case studies performed by IPT are presented in this paper. The trends for the future are to apply monitoring techniques to mechanical components and structures able to alert the possibility of failures before they occur.

Keywords:
failure; fracture; fatigue; flake; fretting

1 Introduction

Since 1907, the time when IPT acquired its first optical microscope for metallography, failure analysis has been an important activity which IPT has always been involved in. The term failure analysis has a broad meaning, but here it will be restricted to the analyses, performed on fractured or cracked mechanical components and structures, intended to determine the causes of the failure. Engineers normally aim at designing machines, engines, and all sorts of mechanical components and structures to be failure proof during their expected lifetime. For that, stress calculation, material selection, manufacturing processes, assembling, and maintenance recommendations are carefully specified according to standards and design criteria which are continuously reviewed. When failures occur, it is not unusual that improvements in new editions of standards, construction codes and operational and maintenance guides occur as aftermath of failure analyses. The obedience to these specifications not only provides a safe operation but normally avoids failures. However, if one or more of the items specified above is not obeyed, the possibility of failure will increase.

Situations in which, even though all the specifications and recommendations are followed by the book, failures can occur and result in accidents. Sometimes the design is correct but, during the assembling or the construction, some simplifications are adopted, or, for example, some misguided action taken by workers not properly trained can introduce defects as arc strikes on structures and rotating parts, misalignment in assembling, disobedience to the design in manufacture, and others, threatening the equipment's performance. Problems as such do not appear necessarily at the startup and at the first hours of operation but later when the equipment is running in a steady state. Other times, a small incident can cause a visually imperceptible damage, as a dent on an originally smooth surface, or a mini or micro bend on an originally straight part subjected to tensile pulsating loading, for example. This kind of a damage changes local stresses, so the component which was professionally designed to resist the operational loading becomes susceptible to develop a fatigue crack even working according to the expected loading.

Sometimes unexpected effects of the environment can become a huge problem. The damage of a pump seal causing a small leakage can lead a surface of a shaft to pitting corrosion, for example. The pit can become a stress raiser able to initiate a stress corrosion crack or a fatigue corrosion crack.

Misalignments of shafts, originally aligned, caused by small movements of the soil can provoke displacements on the foundation of heavy equipment, such as gear boxes coupled to motors, capable to introduce bending loads on shafts not predicted in the design. If the shafts were designed to resist severe torque (when the most important load is torsion) and negligible bending, fracture in consequence of rotating bending due to misalignment can occur. Many times, a proper care in the foundation design and the use of elastic couplings between the motor shaft and the gear-box shaft can fix the problem.

Equipment for high temperature service, which sometimes suffers local temperature increase due to a deficiency on the heat transmission through pipe walls, can suffer local overheating which consequence can be the premature failure due to creep. Equipment designed to work continuously, but used intermittently, can fail with fewer working hours than the predicted in design because it will be more prone to thermal fatigue.

It is not uncommon to have hardened and tempered steel parts that are zinc plated for protection against corrosion to suffer hydrogen induced cracking. The zinc plated layer does protect steel from general corrosion, attracting to itself the anodic reaction, but at the same time, the cathodic reaction on the iron generates hydrogen which, being absorbed by the steel, can cause hydrogen induced cracking on regions submitted to tensile stress.

There are many other situations like those presented above, and it would be impossible to make a complete list of events able to cause failures.

Fortunately, there are solutions for fracture control which means that, if it is not possible to fix all the problems that can lead a component to fracture, it is possible to take actions to avoid it. Preventive and predictive maintenance, nondestructive evaluation, damage tolerance and fitness for service are resources normally used to avoid fracturing. The use of temperature, vibration, stress and strain sensors can provide a continuous monitoring of critical mechanical members, producing data able to indicate if something wrong is going on before the failure occurs. For cracked members, it is possible to control the crack advancing before it reaches a critical size performing a continuous acoustic emission monitoring.

As can be seen, currently, there are technical resources able to reduce the risk of failure to almost zero. They are more or less applied in function of the possible consequences of the failure. If the fracture does not threat human and environmental safety and/or does not imply in significant economic losses, corrective actions as the substitution of a broken bolt,

for example, can be enough. Other times, the failure of only one bolt can be the beginning of a huge disaster indicating that each case shall be individually evaluated.

Since its foundation, IPT has analyzed thousands of fractures of different sorts of mechanical components. In 1912, Hippolyto Gustavo Pujol Junior , the engineer responsible for the acquisition and operation of the first equipment for mechanical testing and microstructural analysis of IPT, published an article on microscopic metallography and thermal analysis (PUJOL, 1912) which was the basis for the course on those subjects, which he taught at Polytechnic School of São Paulo. The consolidation of the capability of IPT to analyze failures occurred after Hubertus Colpaert assumed the management of the laboratory in 1928. In his book on metallography published in 1951, Colpaert (1951) presented several examples of fractured parts analyzed by IPT.

During the first half of 20th Century, railways crossed the State of São Paulo, Brazil, and companies used to request IPT's help when failures of railroad components and trains parts occurred. From mid--fifties to sixties, after Colpaert's death, Alberto Albuquerque Arantes took the responsibility to perform failure analysis at IPT. His extensive background on materials and on mechanics gave him resources not only to evaluate the material properties but also to analyze the loads responsible for fractures. During this time, the role of Arantes analyzing failures of automotive components should be highlighted. These components were being nationalized by the recent automotive industry implanted in Brazil, and Arantes proposed changes in material and in manufacturing processes to obtain the desired properties of com-

ponents which in some cases exceeded them. Still in the sixties, Paulo Sérgio Carvalho Pereira da Silva started his engineering career at IPT and soon assumed Colpaert's and Arantes's heritage (ITO, 2007). Later, Paulo Sérgio and Tiberio Cescon, a former IPT intern advised by Colpaert, taught a new generation of specialists, among them, the main author of this paper, who is proud of having so brilliant teachers. A previous publication on IPT´s failure-analysis case studies (AZEVEDO; CESCON, 2004) presented a list of 22 researchers that performed failure analysis at IPT from 1933 to 2003 and about half of them followed directly or indirectly the teachings of Paulo Sérgio and Tiberio.

Currently, it is possible to say that along its existence, IPT has performed thousands of failure analyses, from tinny parts like hypodermic needles to huge parts like crankshafts of stationary engines of thermoelectric power plants; from small LPG containers for domestic use to huge pressure vessels of petrochemical industry. IPT customers are normally private

companies, state companies and the government, but sometimes, IPT also attends private individuals. Currently, IPT performs failure analysis of a different sort of equipment and structures for the whole country (Brazil) and overseas if it is requested to.

Due to a trust relationship established between IPT and customers, the information contained on IPT reports are confidential, and cannot be spread out to the public. The exceptions occur only when the customer provides a written permission allowing IPT to divulge the content of the reports, normally publishing papers on the subject. This does not mean that the results of projects requested by the District Attorney or the Court of Justice cannot become public because, in these cases, the reports are attached to the lawsuit that can be consulted by interested persons.

This article intends to present some examples of case studies on failure analyses performed by IPT without exposing any customer. Because of that, much information of the investigations, including procedures, data, calculations, and the customer itself will not be presented.

The early case studies performed by IPT were mostly related to defective parts, like rails and train wheels presenting internal or surface defects, inappropriate welding on hardened and tempered parts and so on. It is important to remember that, at that time, the only nondestructive test available was the visual inspection. Radiography, magnetic particles, eddy current, ultrasonic testing, and other nondestructive testing, which today can assure the soundness of parts and structures, had not been developed or were not easily available then. Chemical analysis and mechanical testing were used in quality control, but they were unable to determine if a given part was defective or not. Metallography could, and still can detect shrinkage and pores in castings and forging and rolling laps. Nevertheless, metallography is destructive, and it would not be applied to parts that were going to be put in service. On the other hand, metallography used to be and is still one of the most powerful resources in failure analysis. In the past, many failures could be attributed to the material's quality or processing which could be easily identified by metallography and still can nowadays.

The application of the scanning electron microscopy in failure analysis started around 1960 and, at IPT in the 1970's, caused a revolution because it not only made it possible to determine fracture micro-

-mechanisms but also it was able to provide local chemical analysis of precipitates, inclusions and products of corrosion or oxidation, when equipped

with EDS and WDS. X-ray diffraction, Auger spectroscopy and transmission electron microscopy can also be applied in failure analysis, but the solution of most of the cases does not require them.

Currently, many industries apply severe rules in quality control in mass production of several parts used in different applications reducing much the possibility of failures. However, it does not apply to big parts or structures which, most of the times, are produced in small quantities and sometimes just one piece. In these cases, the material properties or the quality evaluation based on nondestructive testing are applied individually to each part or structure.

2 Case studie

It is impossible to present studies of failure analysis performed at IPT encompassing all sorts of materials, structures and mechanical components. The few case studies to be presented ahead are not necessarily the most important but they were chosen because they were familiar to one of the authors since he was part of the teams that performed the analyses. The choice of what to present was not easy because along its lifetime IPT has analyzed failures for different kind of industry. Following, a tentative list of grouping the industrial branches for which IPT has performed failure analyses is presented:

- *Agriculture;*
- *Air Transportation;*
- *Automotive;*
- *Cement;*
- *Chemical;*
- *Civil Construction;*
- *Electric Power;*
- *Food;*
- *Metallurgical;*
- *Mining;*

- *Oil and Gas;*
- *Petrochemical;*
- *Pulp and Paper;*
- *Railroad;*
- *Steelmaking;*
- *Sugar and Alcohol.*

2.1 Case studies related to railway and trains

2.1.1 Longitudinal cracking of a rail due to residual stress

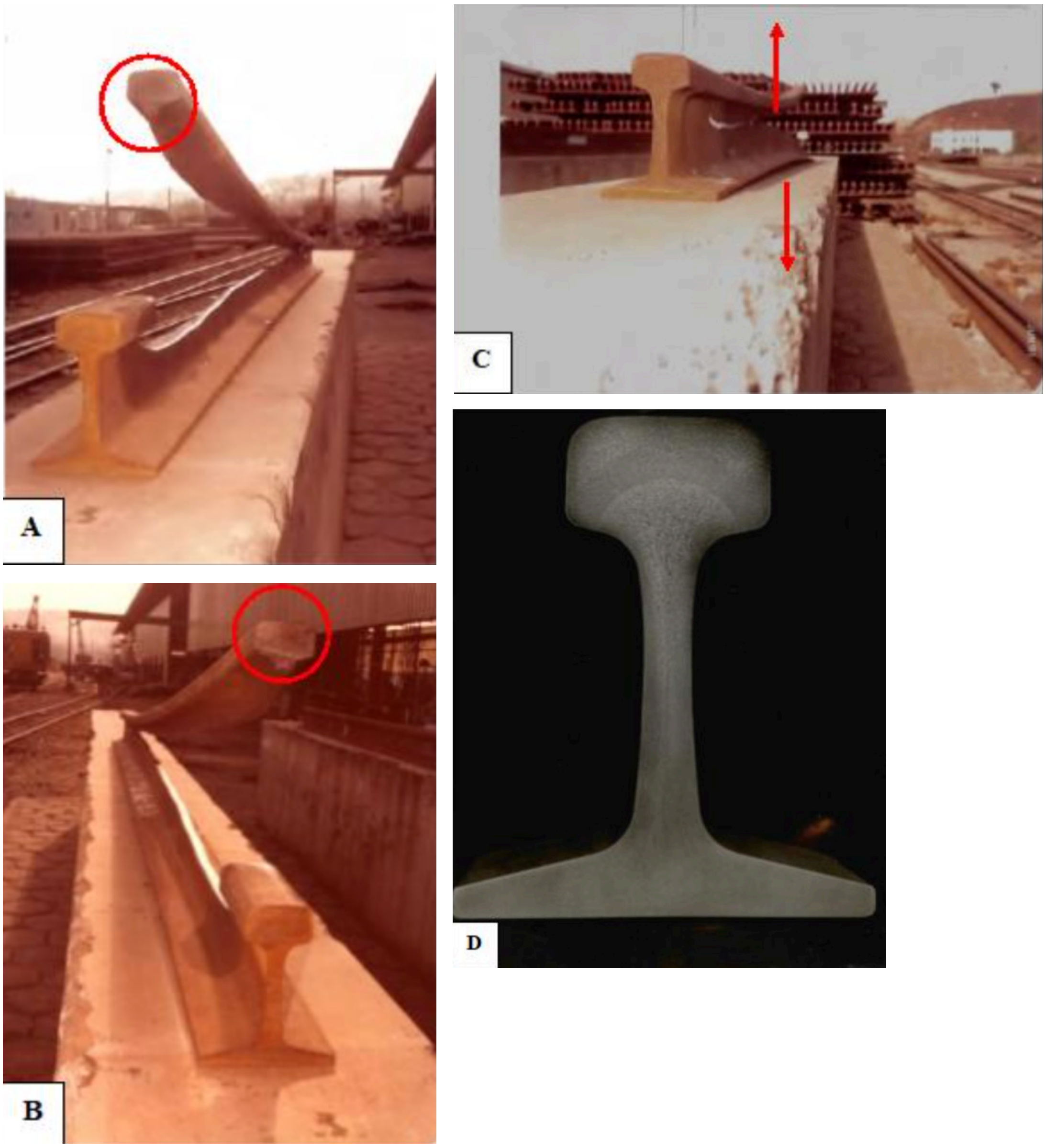
As mentioned before railways were the one of the first kind of industry to request failure analyses to IPT. There are so many cases that it would be impossible to enumerate and present them in a single article. Fatigue of rails initiated in hydrogen flakes (fish eyes) and brittle fracture of wheels initiated in surface cracks caused by local heating due to friction when the wheel blocked by the brake slid on the rail, used to happen frequently in the past (ITO, 1994).

An astonishing longitudinal cracking along the rail web caused by residual stress during the assembling on the track requires to be reported to become unforgettable (INSTITUTO DE PESQUISAS TECNOLÓGICAS, 1981a). ***Figure 1*** *shows a surface quench hardened rail that cracked during its assembling on the track. The rail was being transversally cut-off when suddenly it cracked longitudinally along the web in consequence of residual stress. Details (A) and (B) of* ***Figure 1*** *show the displacement of approximately 1 m, between the opposed surfaces of the crack in the cut region. The arrows in detail (C) point to the center of curvature acquired by the head and the rail base after the cracking. The displacement between the crack opposed surfaces and the curvature of the head and rail base occurred in consequence of the stress relieving of the residual stresses probably introduced during the heat treatment of the rail head and the cold straightening that followed it. Detail (D) presents the macrography of a transverse section of the rail, showing the depth of the local quench hardening of the head.*

2.1.2 Fracture of a rail due to hydrogen absorbed during the steelmaking process

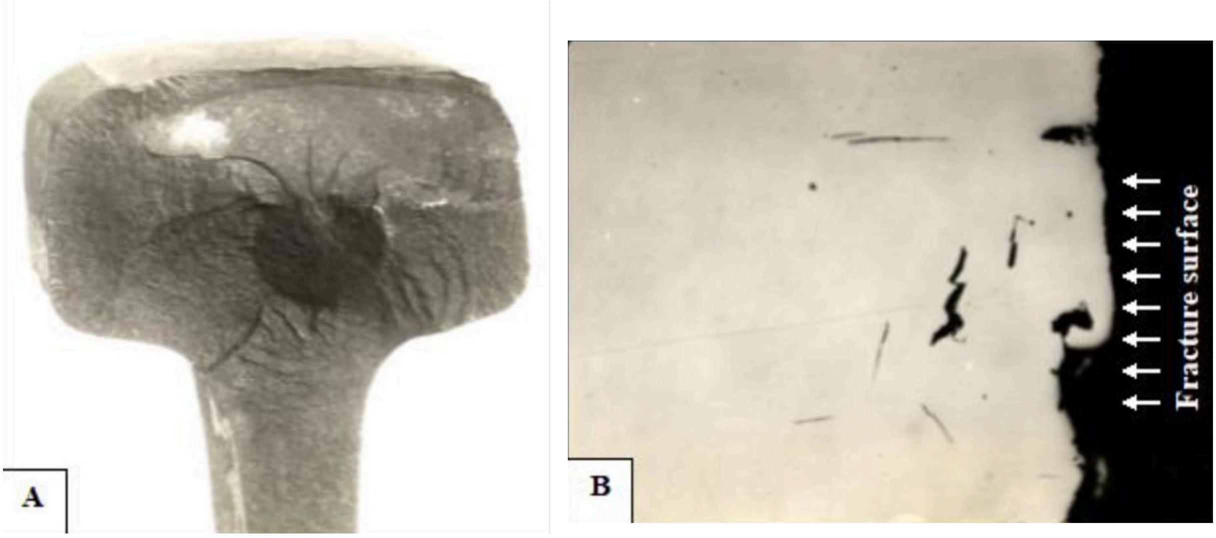
Figure 2 *shows a transversal fracture of a rail initiated in a consequence of hydrogen embrittlement due to deficient degassing during the steelmaking processing (INSTITUTO DE PESQUISAS TECNOLÓGICAS, 1981b). The metallographic analysis of a section approximately perpendicular to the dark* *elliptical area of the fracture in the rail head, known as fish-eye (AMERICAN SOCIETY FOR METALS HANDBOOK COMMITTEE, 1975; POLUSKIN, 1956), observed in Figure 1 (A), presented hydrogen flakes showed in Figure 2 (B). The alternating vertical loading, applied to the rail due to the regular transit of trains caused fatigue propagation inside the head, from the fisheye area. The fracture occurred when the crack reached its critical size.*

Figure -1 – Aspect of a rail cracked longitudinally along the web during a cut along the transverse section. (A) and (B) Observe the displacement occurred after the rail cracking. The region that was being cut is encircled in red. (C) Under this angle of view it is possible to observe the curvature occurred in the head and in the rail base which centers of curvature point to opposed directions. (D) Aspect of the macrostructure of a transverse section of the rail showing the heat-treated region of the rail head.



Source: Instituto de Pesquisas Tecnológicas (1981a)

Figure 2 – Aspect of a rail fractured transversally in consequence of hydrogen embrittlement. (A) The circular area in the rail head is known as fisheye occurs when hydrogen dissolved in steel in liquid state is not properly eliminated during the steel refining. (B) This photomicrography, taken from a rail longitudinal section passing through the fisheye region, presented internal cracks known as hydrogen flakes.

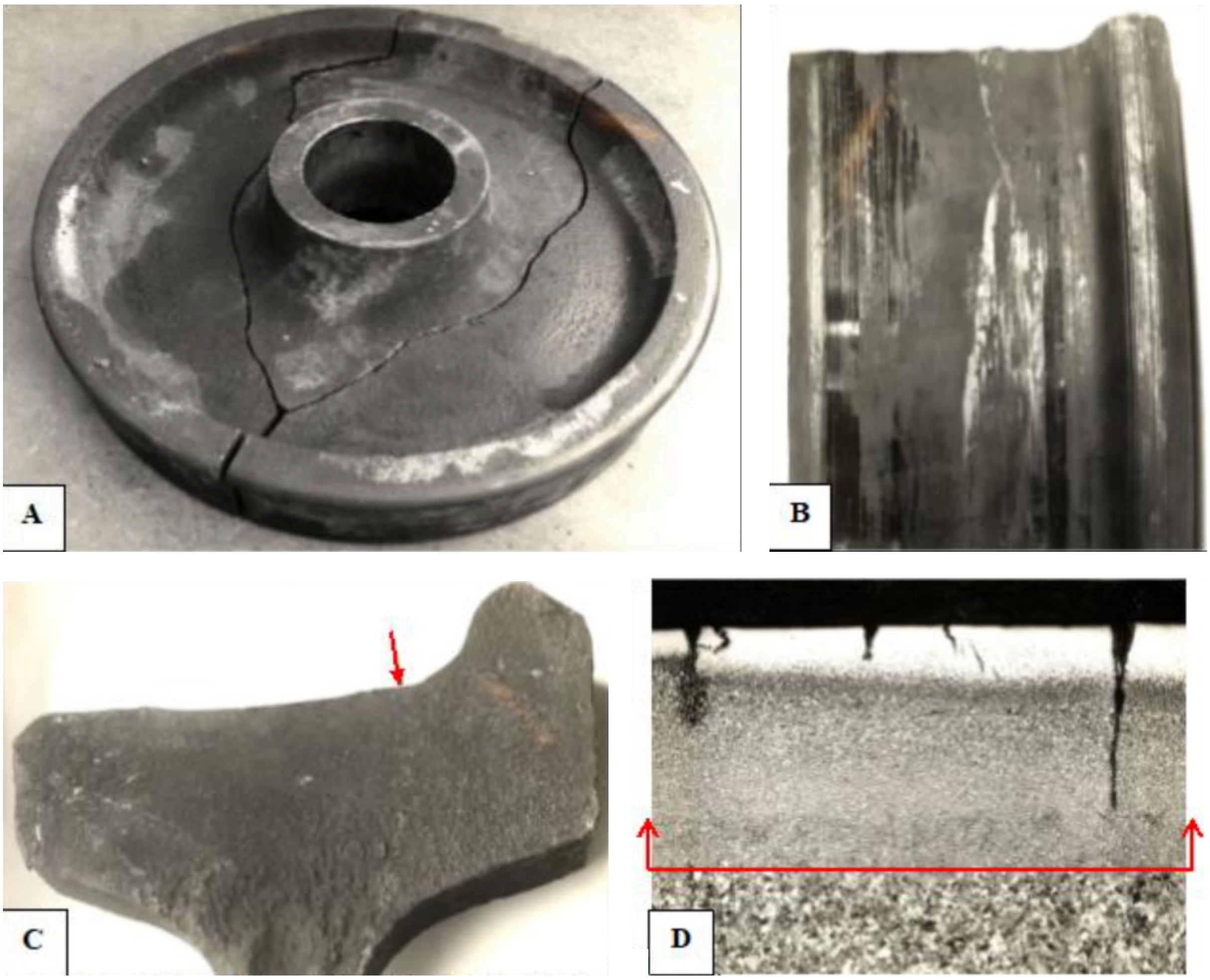


Source: Instituto de Pesquisas Tecnológicas (1981b)

2.1.3 Fracture of a wheel due to thermal cracking on the rolling surface

Figure 3 *presents a train wheel that fractured in consequence of thermal cracks on the rolling surface (INSTITUTO DE PESQUISAS TECNOLÓGICAS, 1981c). The wheel blocking occurred during braking led the wheel to slide on the track. The white layer, observed in* ***Figure 3*** *(D), is constituted of untempered martensite caused by the temperature rise caused by the heat generated by the friction between the wheel surface and the track surface. The heating rose the temperature of the wheel surface up to the austenitic field. The quenching provided by the heat drained from the rolling surface to the wheel bulk caused cracking. The fracture initiated in one of these cracks.*

Figure 3 – (A) General aspect of the fractured wheel. The fracture began at the rolling surface, propagated along the rim and bifurcated around the hub. (B) Scratching can be observed on the wheel's rolling surface. (C) Aspect of the fracture surface. The arrow points to region of fracture initiation. (D) Microstructure of the material observed on a section perpendicular to the fracture surface. The region above the red line suffered microstructure change in a consequence of local heating generated by the friction between the wheel and the track. The whitish region is constituted of untempered martensite. The cracks initiated on the wheel surface due to thermal shock propagated in consequence of thermal fatigue and/or thermal-mechanical fatigue. Above the red line, there is the heat affected zone caused by the heat generated by friction between the wheel and the track. Below the red line, the material presents a regular microstructure for the wheel, constituted of pearlite. Magnification: 50X; etchant: Nital.

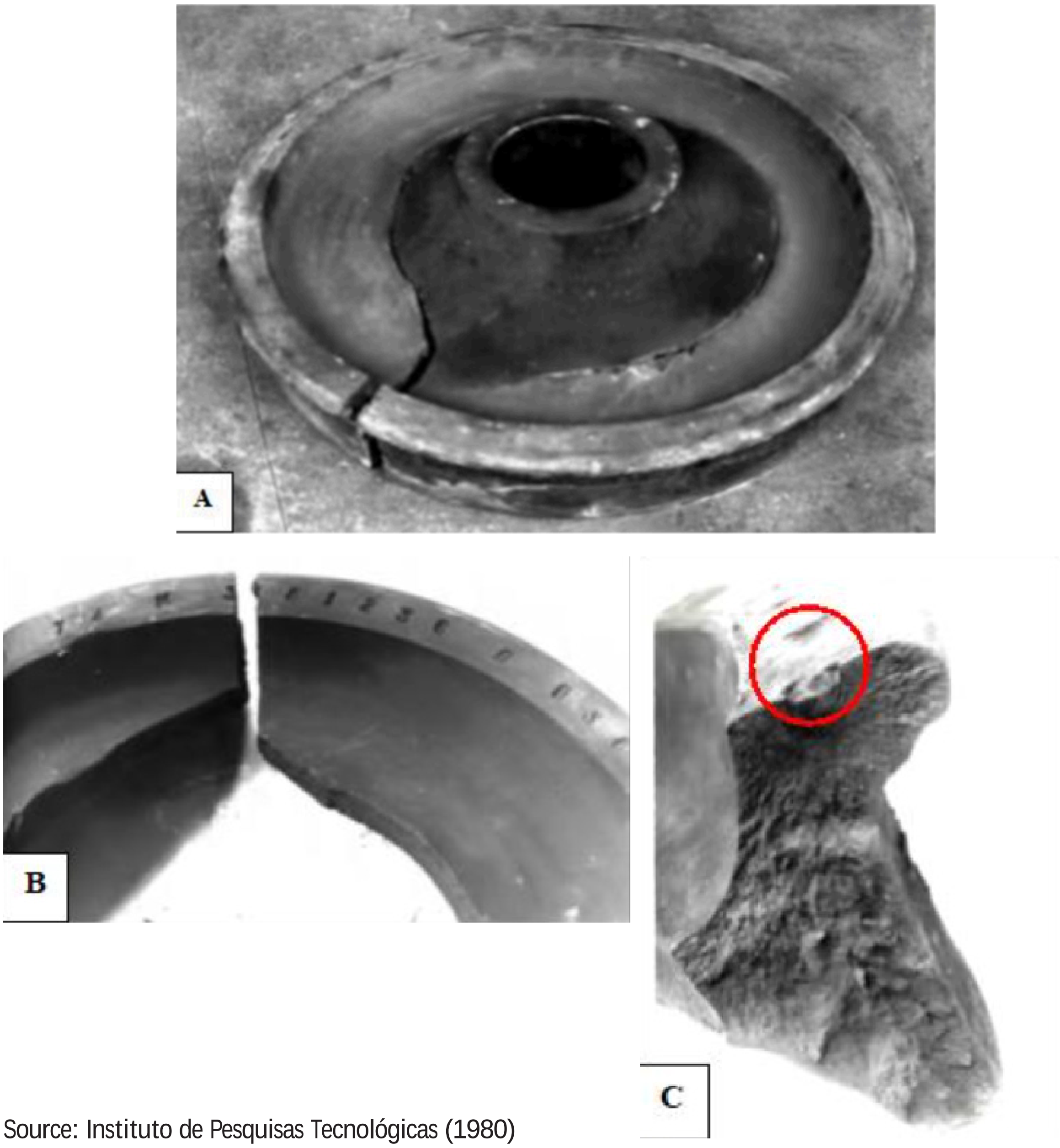


Source: Instituto de Pesquisas Tecnológicas, (1981c)

2.1.4 Fracture of a wheel due to a too sharp identification mark

Figure 4 (A) presents a train wheel fractured as consequence of a manufacturing defect (INSTITUTO DE PESQUISAS TECNOLÓGICAS, 1980). The stress concentration caused by a too deep and sharp identification mark, observed in Figure 4 (B), provided conditions

Figure 4 – (A) General view of the fractured wheel. It can be observed that the hub detached from the wheel. (B) Aspect of rim side (flange) where the identification numbers and letters were stamped. It can be observed that the fracture passes through one of the identification marks. (C) The area outlined by the red circle shows fatigue beach marks spreading out from the tip of an identification mark. Radial marks typical of brittle fracture propagated from the fatigue area.

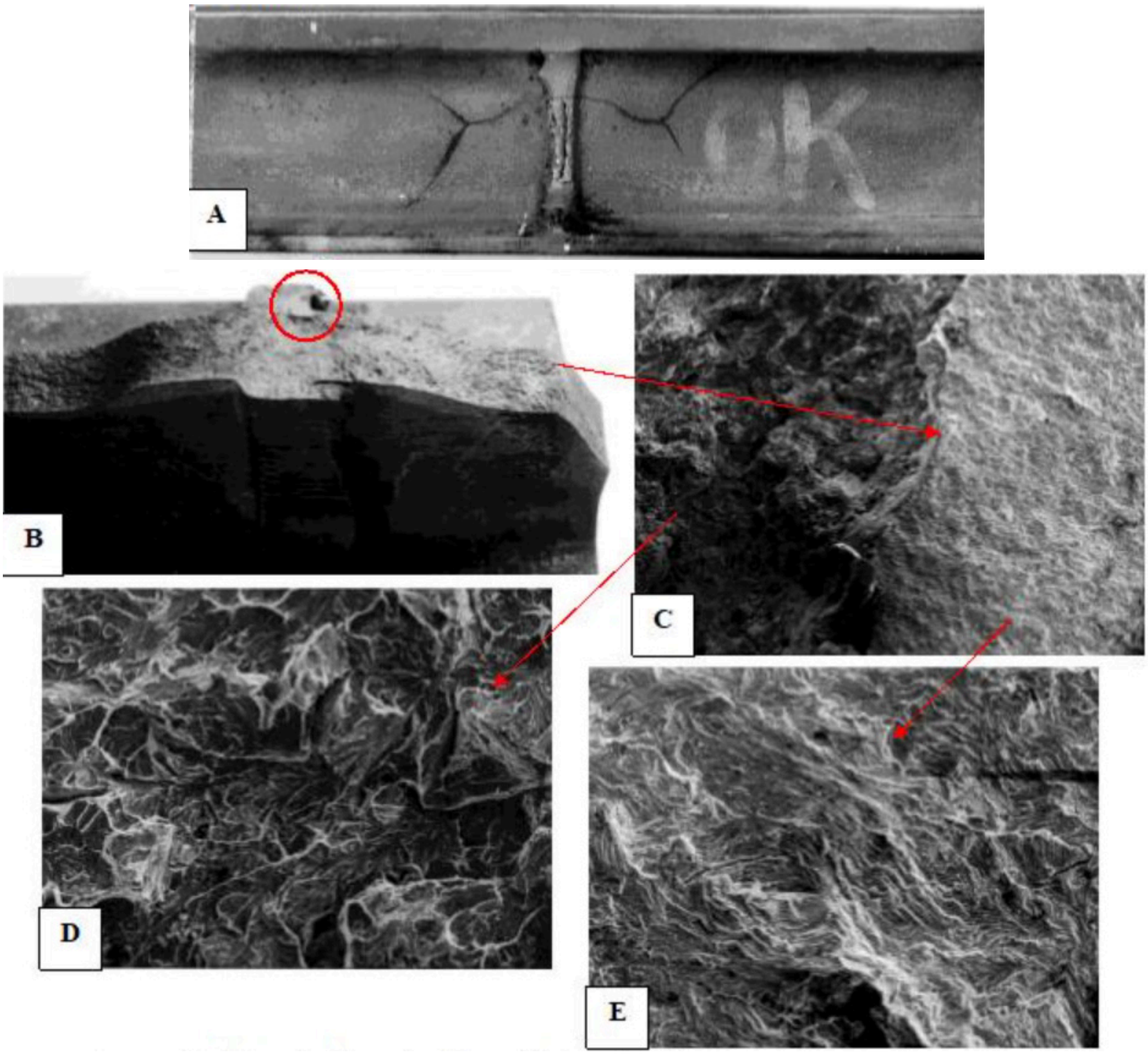


Source: Instituto de Pesquisas Tecnológicas (1980)

2.1.5 Cracking of a rail butt weld joint due to multiple causes

Figure 5 (shows a rail butt weld joint cracked in service and removed from the tracks before fracturing (INSTITUTO DE PESQUISAS TECNOLÓGICAS, 1990). Figure 5 (A) shows the aspect of the joint after a liquid penetrant testing. It can be seen that the crack presents a pattern almost symmetrical in relation to the weld, in which a longitudinal crack splits in both of its ends. Figure 5 (B) shows the aspect of the exposed surface of the crack after the rail was properly cut. The region outlined by circle presents a defect in the weld flash that triggered the failure process. Firstly, a small fatigue crack initiated on the defect became unstable and suffered a sudden longitudinal propagation. The stresses responsible for this step were due to a combination of the stress caused by the lateral component of the load applied by the wheel flange on the track and the residual stress due to an inefficient or a lack of stress relieving after welding. The longitudinal propagation of the crack stopped when the stress relieving caused by its own propagation lead it to arrest. After this step, the rail became more compliant allowing the development of four fatigue cracks, two each side. Figure 5 (C) show the intersection between longitudinal crack and one of the two cracks that propagate in directions approximately at 45 degrees from the longitudinal crack. From Figure 5 (C) two arrows point to two photos of secondary electron image taken in a scanning electron microscope. Figure 5 (D) presents the microfractographic aspect of the surface of the longitudinal crack that shows cleavage, and Figure 5 (E) presents the microfractographic aspect of the slant crack that shows fatigue striations. The complete process can be described as the initiation of a small fatigue crack in a weld defect due to the lateral loading, applied by the wheel flange on the rail combined with the residual stress due to welding, lead the structure to reach the material's KIc generating the longitudinal crack. The longitudinal crack was arrested due to the relief of the residual stress due to the own cracking. After that, the torsion moment due to the lateral component of the load applied on the rail by the wheels caused two fatigue cracks initiated at each end of the longitudinal crack. This is a case in which no accident occurred because the crack was found during the ultrasonic inspection of the tracks before the rail fracturing. The solution of the problem required a better quality control of the weld to avoid and or to remove defects, the stress relieving after welding to reduce the possibility of cracking, and the periodical inspection of the rails by NDT to find eventual cracking occurred in service.

Figure 5 – (A) Overall view of the weld joint. The cracks were revealed by liquid penetrant. (B) Aspect of exposed surface of the horizontal crack and one slant crack. The circled region indicates a weld defect and around it a small smooth flat area of fatigue. The chevron marks observed on the longitudinal crack surface point to the weld region. (C) This picture taken with low magnification in a scanning electron microscope shows the corner between the longitudinal crack and the lower slant right crack. (D) Secondary electron image of the surface of the longitudinal crack showing cleavage. (E) Secondary electron image of the slant crack showing fatigue striations.



Source: Instituto de Pesquisas Tecnológicas (1990)

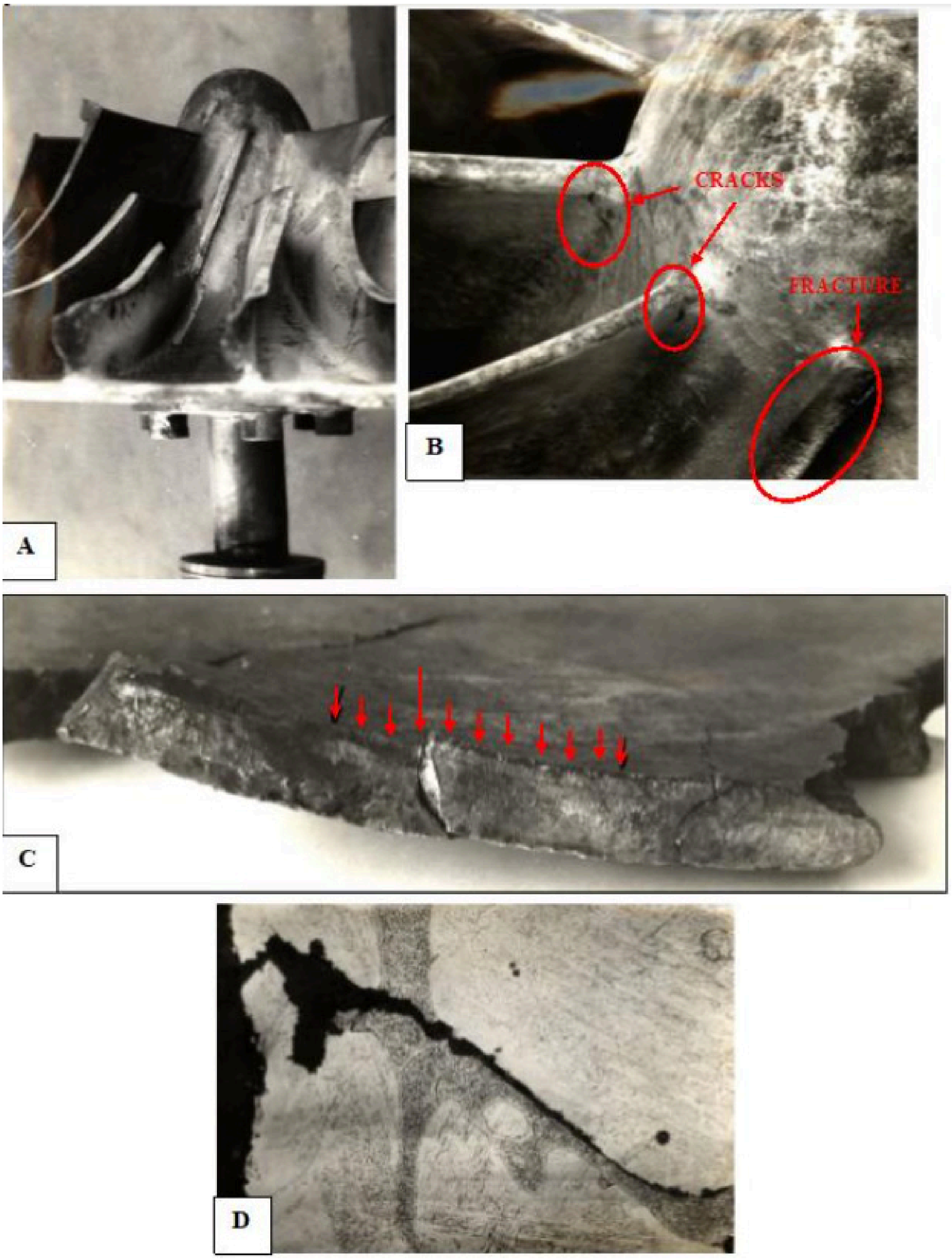
2.2 Cases related to steelmaking equipment

2.2.1 Corrosion fatigue in a rotor of the first stage of an oxygen plant turbo compressor

The rotor of the first stage of an oxygen plant turbo compressor of a steelmaking company, that had its blades fractured, worked under a severe environment due to air pollution (INSTITUTO DE PESQUISAS TECNOLÓGICAS, 1979).

The rotor was made of CB-7Cu, the cast version of the 17-4-PH precipitation hardening stainless steel. ***Figure 6*** *(A) shows an overall view of the rotor and in* ***Figure 6*** *(B); two cracks detected by a liquid penetrant test on the base of the blades near a fractured blade can be observed.* ***Figure 6*** *(C), which shows the fracture surface of a blade detached from the rotor, presents hatched marks typical of fatigue cracks initiated in stress concentration regions.* ***Figure 6*** *(D) shows a photomicrography of a section passing through one crack initiated in a corrosion pit on the blade surface. The WDS analysis performed on the corrosion product in a JEOL JXA-50A Electron Probe Micro-analyzer revealed the presence of the elements oxygen (O), sulfur (S) and chlorine (Cl) inside the pit. The analysis of the water suspension prepared with 5 % of the solid residue removed from the inside of the rotor housing revealed 2.7 pH and chloride and sulfate concentration of 0.07 % and 50.2 %, respectively. The steelmaking plant was near the ocean, the air presented high concentration of SO2 and, before being compressed, the air was simply dry filtered. The humidity and salt from the sea air, associated to SO2, generated in the blast furnace and in the coke plant, provided the condensation of a corrosive solution inside the compressing chamber during the compression. Since pitting corrosion is favored by the exposition of the steel to stagnant contaminated water, it probably occurred during periods in which the compressor was off. The resultant pits became stress raisers responsible for the several points of fatigue initiation indicated by the steps on the fracture surface presented in* ***Figure 6*** *(C).*

Figure 6 – (A) General view of the rotor showing fractured blades. (B) Two cracks detected by liquid penetrant test on blades near a fractured blade. (C) Visual aspect of the fracture surface. The arrows point to hatched marks on the fracture surface typical of fatigue initiation at stress concentration points. The step pointed by the longer arrow indicates a region in which two fronts of fatigue propagation merged. (D) Aspect of the microstructure of a section that crosses a crack propagating from a corrosion pit.



Source: Instituto de Pesquisas Tecnológicas (1979)

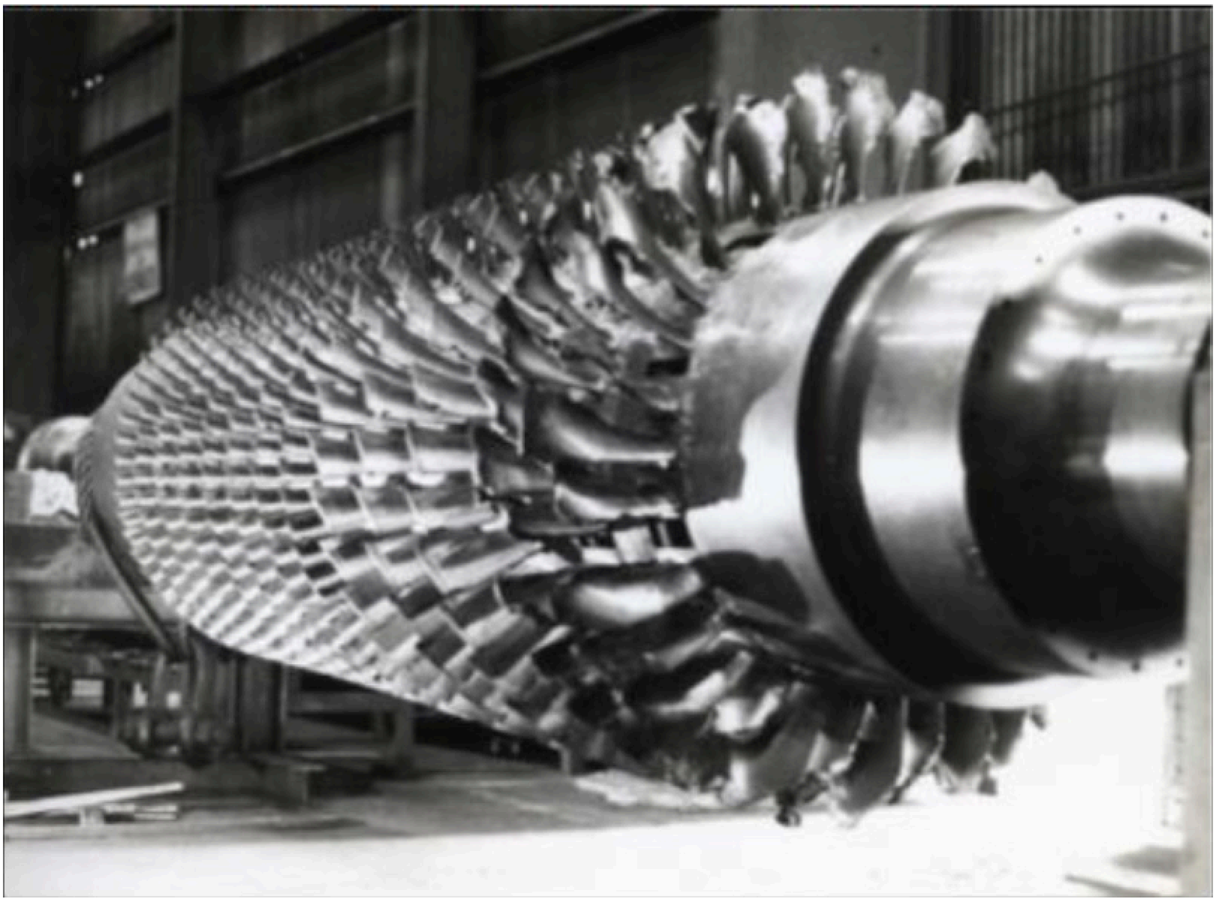
2.2.2 Fracture of blades of an axial compressor that fed Cowpers

The fracture of a few AISI 310 stainless steel blades of the rotor of an axial air compressor almost caused a blast furnace shut off (INSTITUTO DE PESQUISAS TECNOLÓGICAS, 1991a). The compressors were used to feed Cowpers that preheated the air dispensed to the blast furnace tuyères.

The steelmaking company had only two axial compressors for the service, and the other that was scheduled for maintenance could not stop working before the failed one was fixed or substituted. Had the accident of the first compressor occurred just after the second compressor shutdown, the air supply for the blast furnace would have stopped condemning it to freezing.

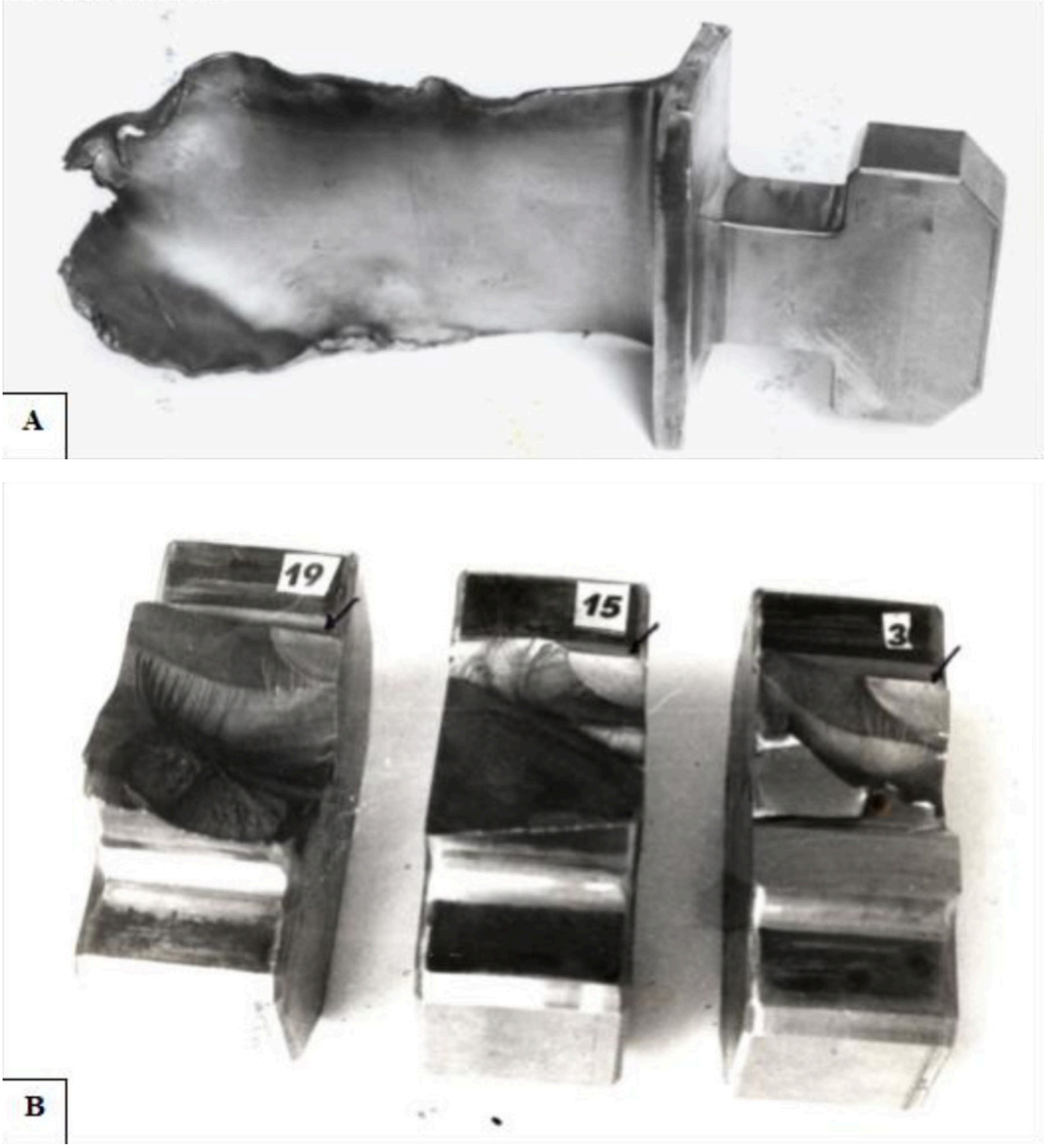
***Figure 7** shows a general view of the compressor rotor after the failure. Six blades suffered fracture, three of the first stage, and three of the second stage of compression. The pieces of blades, detached after fracturing, hit other blades damaging not only most of the moving blades that were attached to the compressor shaft but also the stationary blades attached to the compressor case. **Figure 8** shows the typical aspect of the fracture occurred in the blades.*

Figure 7 – Overall aspect of the failed rotor of the axial compressor.



Source: Instituto de Pesquisas Tecnológicas (1991a)

Figure – 8 – (A) Aspect of one blade of the first stage of the compressor damaged due to impact against fractured blades. (B) Aspect of fracture surface of three blades showing a similar pattern. The arrows point to the fracture of the three blades initiated near the corner between the neck and the fracture surface.

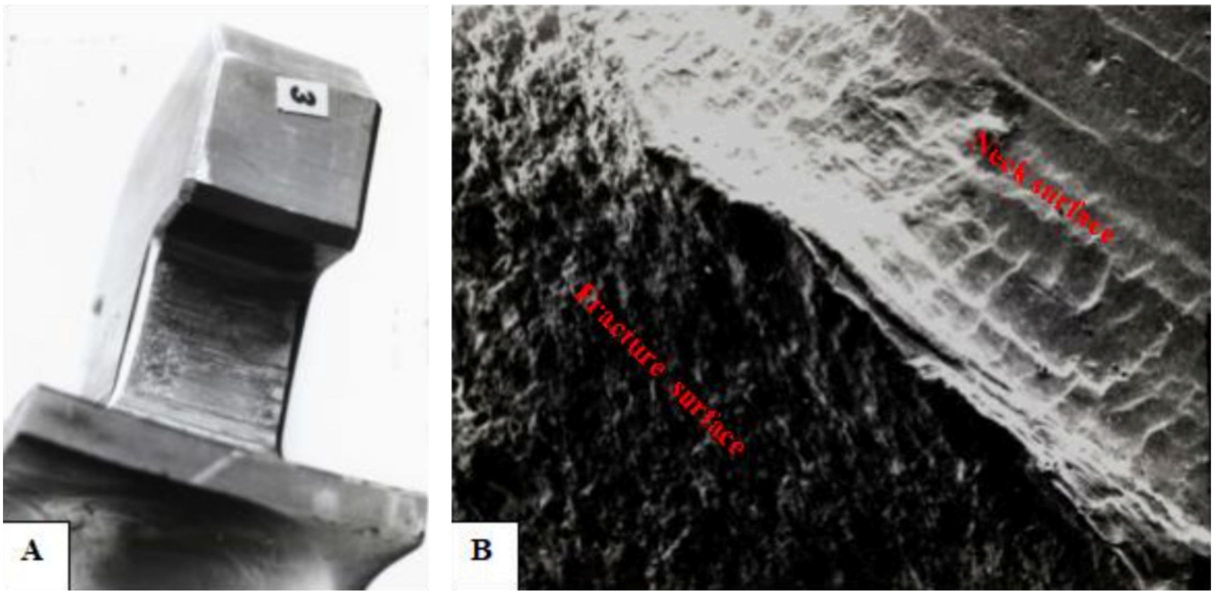


Source: Instituto de Pesquisas Tecnológicas (1979)

The examination of the fracture surfaces presented in Figure 8 revealed that the fracture occurred due to fatigue. **Figure 9** *(A) shows the typical aspect of the blade's neck surface that contacted the assembling groove of the rotor's shaft. The neck's surface was damaged by fretting, caused by micro movements between the blade and the shaft due to the vibration occurred in service. The same damaging was observed on the neck's surface of all blades of stages I and II.* **Figure 9** *(B) shows the typical low magnification secondary electron image of the intersection between the blade surface and the fracture surface. The damage caused by the friction on the blade surface is observed.*

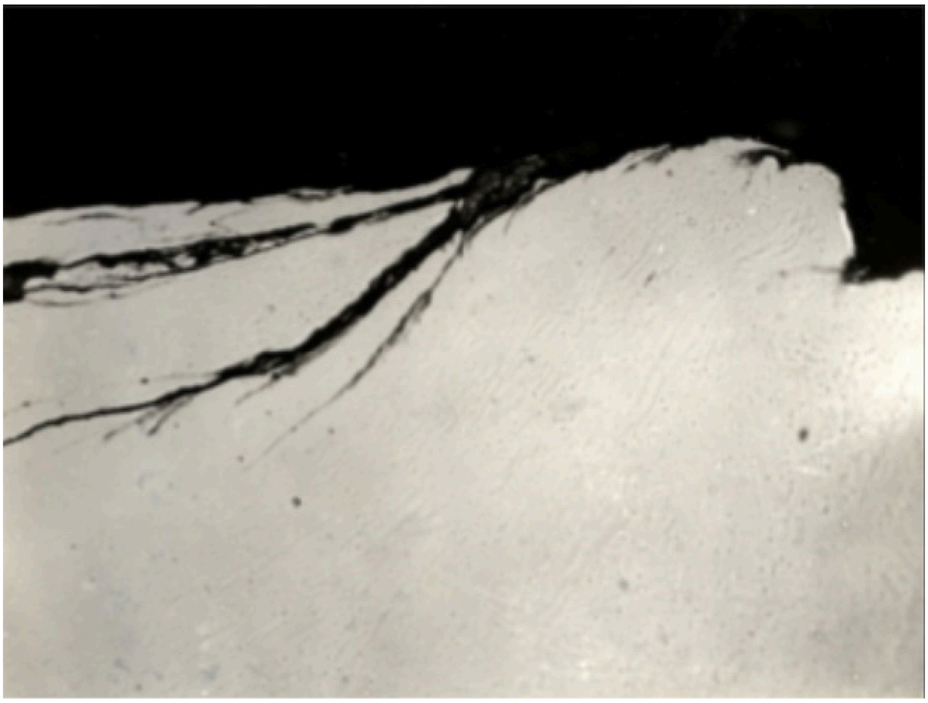
An unetched section, perpendicular to the corner between the fracture surface and the blade surface observed in **Figure 9** *(B), presented in* **Figure 10***, shows deformation laps on the blade neck surface caused by fretting.*

Figure 9 – (A) Aspect of a blade neck's surface showing scratching caused by friction against the shaft's groove surface. (B) Secondary electron SEM image showing the intersection between a fracture surface and a blade surface showing damage caused by friction on the neck surface.



Source: Instituto de Pesquisas Tecnológicas (1991a)

Figure 10 – Aspect of a section observed by optical microscope perpendicular to the corner between the fracture surface and the blade's neck showed in Figure 9 (B) showing deformation laps on the neck surface. Unetched. Magnification 500 X.



Source: Instituto de Pesquisas Tecnológicas (1991a)

The major cause of the fracture was the too small clearance between the blade's neck surface and the shaft's groove surface which allowed the contact between the surfaces and consequently fretting. The stress responsible for the fatigue was due to vibration combined with the stress due to the radial load caused by the centrifugal force on the blades estimated in about 40 % of the yield stress of the material (520 MPa) for the blades of stage I of the compressor.

2.3 An example of rupture of containers for liquefied gases

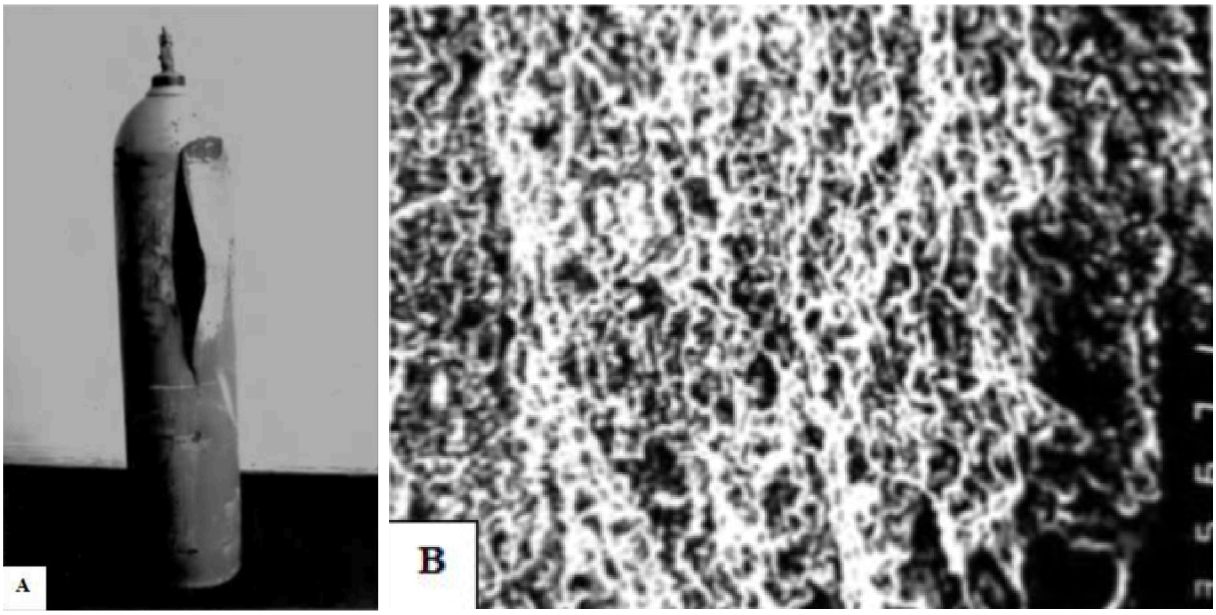
Many gases under pressure are in equilibrium liquid/gas states at room temperature. In those cases, the volume of the container is filled with a mass of product partly in liquid state and partly in gas state. Since there is gas and liquid inside the container, the internal pressure is the vapor pressure of the substance for the temperature at which it is maintained. In this condition (constant volume), a temperature rising increases the volume of the liquid fraction and a temperature lowing reduces the volume of it. If the container is overcharged, it is possible for the whole volume of the container to be totally filled with liquid. It can be found in thermodynamics data books that the compressibility of liquids is much smaller than the compressibility of gases. If the container is totally filled with liquid, liquid

expansion due to heating will stress the container walls much more than if the container is filled with liquid in equilibrium with gas at the same temperature.

Normally, to avoid overpressure of the container, it is equipped with safety valves. There are different kinds of safety valves, those limited by pressure and those limited by temperature. Valves that open above a defined pressure can simply be rupture discs made of defined thickness and material resistance that once ruptured, release all the gas inside the container. Another type of pressure limiting valve is provided with a spring that maintains it close until the opening force due to the internal pressure overcomes the shutting force applied by the spring. Once opened, the valve releases gas just enough to relief the pressure in excess, and closes. There are valves controlled by temperature made of low melting-point alloys that melt when it is reached, releasing all the gas.

***Figure 11** (A) presents a cylinder for chlorine gas that, after being exposed to sun during a summertime day on a truck bucket, had a sudden rupture (INSTITUTO DE PESQUISAS TECNOLÓGICAS, 1991b). The inhalation of the gas by a person that was near the container led him to death. The material analysis did not reveal any quality problem in the cylinder and the fracture was 100 % ductile as can be observed by macroscopic deformation showed in **Figure 11** (A), and microscopically by the dimples revealed in a scanning electron microscope secondary electron image presented in **Figure 11** (B).*

Figure 11 – (A) Aspect of the cylinder after rupture. It can be observed that the rupture was accompanied by macroscopic plastic deformation. (B) Secondary electron image of the fracture surface observed in a scanning electron microscope. The fracture surface is constituted only with dimples.v



Source: Instituto de Pesquisas Tecnológicas (1991b)

The cylinder volume was 50 liters and was able to be filled up to 68 kg of chlorine. Chlorine is a substance that, as LPG and CO$_2$, under pressure, can be kept liquefied at room temperature. At constant temperature, the pressure is maintained constant as long as there is gas and liquid simultaneously inside the container. The problem occurred because the cylinder was overloaded leading the cylinder to be totally filled with chlorine in a liquid state and it was equipped only with a fusible safety valve that should open when the temperature reached 70 °C. Because the cylinder was too full, it reached a rupture pressure much before the melting temperature of the fusible valve was reached. Calculations in the report demonstrated that an overload of 5 kg of chlorine would be enough to lead the cylinder to yield at 30 °C. Other cylinders of the same lot were found with more than 5 kg overload sustained the assumption that the failed cylinder was overloaded. The ductile fracture, the obedience of the material to the specifications and the absence of manufacturing defects in the container indicate that the material quality should not be responsible for the failure.

The use of an inappropriate safety valve, the overloading during the cylinder fill up and the heating caused by the sun exposure caused the cylinder rupture. The simple obedience to the limit loading and proper storage of the chlorine cylinder would have avoided the accident.

2.4 Cases related to new material processing

2.4.1 Fracture of a concrete prestressing steel bar

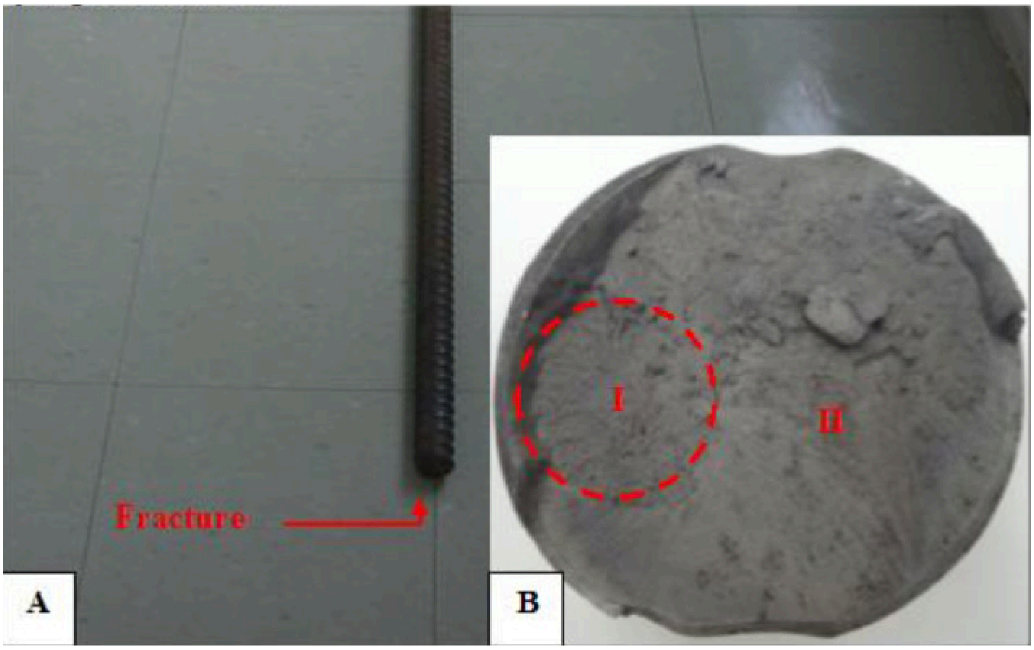
The steelmaking processes have been developed in such a way that currently it is rare to find steels that do not obey the specified chemical composition. The improvements on steel refining lead the content of impurities like sulfur and phosphorus to levels at least one order of magnitude below the minimum specified long ago by standards that have been valid until nowadays. In the past, when out of the specification, these impurities used to be responsible for low performance of steels. However, there are a few situations in which a too low percentage of sulfur can become a problem. Too low sulfur can make hardened and tempered steel prone to develop a defect named fisheyes due to the action of low hydrogen levels that, in the past, were considered safe. It has been found that some sulfur can be helpful to protect steel against hydrogen (FRUEHAN, 1997). Depending on the application, it is possible to be necessary to establish not only the maximum level but also a minimum level of sulfur content.

***Figure 12** shows a quenched and tempered rebar used for prestressing concrete that fractured due to hydrogen (INSTITUTO DE PESQUISAS TECNOLÓGICAS, 2014). The material chemical composition obeyed the specified by ISO 6934-1 [INTERNATIONAL ORGANIZATION FOR STANDARTIZATION, 1991], but the sulfur content was 0.006 %, or one order of magnitude below the maximum established by the standard (0.040 %). The fracture surface showed in Figure 12 (B) presents an almost circular area from which the fracture propagated.*

***Figure 13** shows secondary electron images (SEI) of Regions I (fracture initiation) and II (fracture propagation) indicated in **Figure 12** (B). **Figure 13** (A) shows that the aspect of*

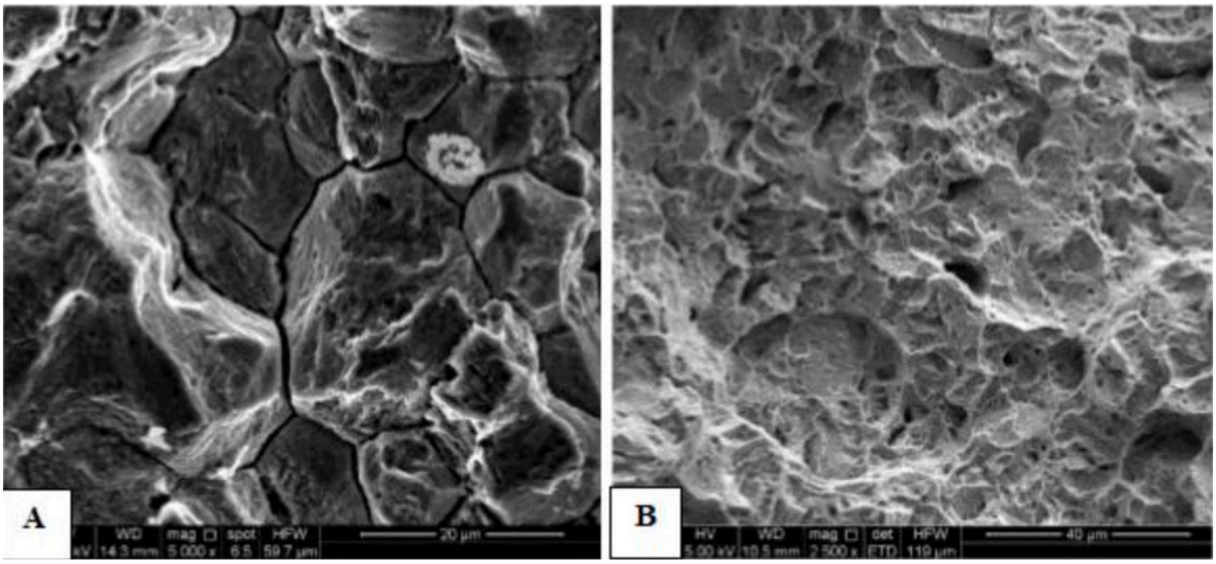
*the fracture of Region I is intergranular with secondary intergranular cracks, typical of hydrogen embrittlement. **Figure 13** (B) shows the aspect of Region II of the fracture surface which is constituted of a mix of cleavage and dimples, sometimes, named quasi cleavage.*

Figure 12 – (A) Fractured rebar for pre-stressed concrete. (B) Aspect of the fracture surface. The circled area of the left side of the fracture outlines a fisheye due to hydrogen embrittlement.



Source: Instituto de Pesquisas Tecnológicas (2014)

Figure 13 – (A) Aspect of fracture surface observed by scanning electron microscopy of Region I of Figure 10 showing intergranular fracture and secondary intergranular cracks. (B) Aspect of fractured surface observed by scanning electron microscopy of Region II of Figure 1. Mix of cleavage and dimples - quasi cleavage.

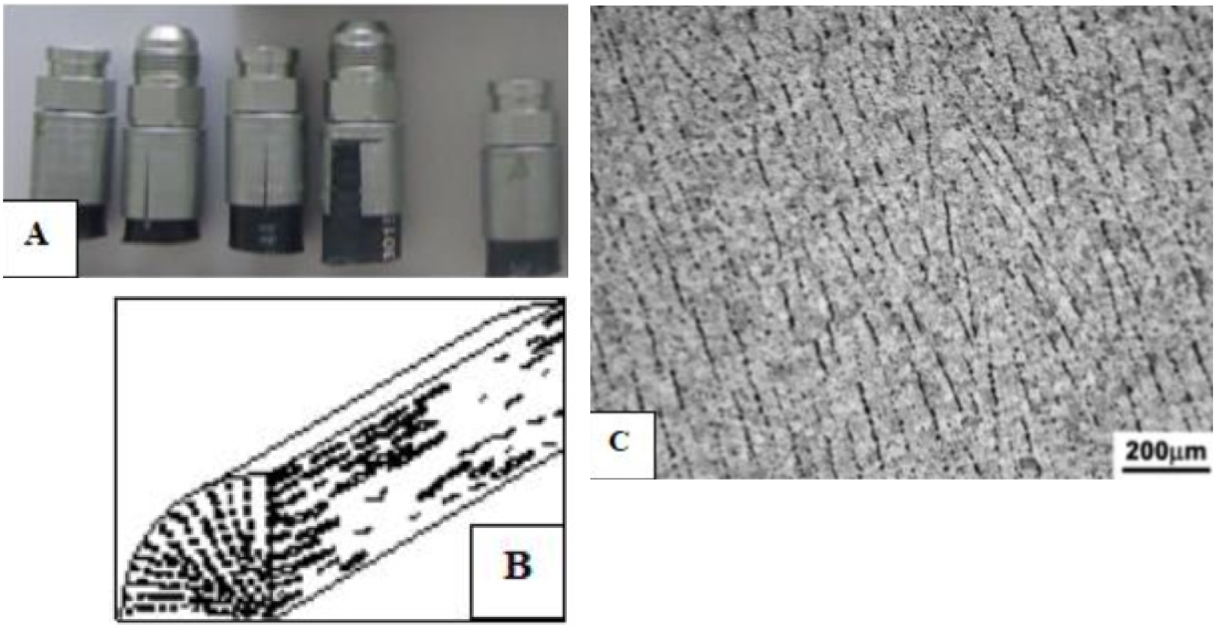


Source: Instituto de Pesquisas Tecnológicas (2014)

***Figure 14** shows another example of a material that had its implicit properties reduced by new processing (INSTITUTO DE PESQUISAS TECNOLÓGICAS, 2009). The parts observed in Figure 14 (A) were high pressure hose couplers. The regular process to make the couplers was to machine bars of resulfurized steel. The assembling operation by spiking the coupler on the hose used to be applied for a long time without so many cracking events.*

*When the manufacturer started to use continuous cast hot-rolled resulfurized steel bars, the cracking during the spiking of the couplers on the hoses began to become epidemic. The cause was the percentage of area reduction during the rolling of the new steelmaking process was not high enough to eliminate the radial orientation of the inclusions generated in the solidification as shown in **Figure 14** (B). The hot-rolled bars passed in all tests long ago established according to standards. However, the new steelmaking process not only caused radial columnar grain grown along the radial direction, orienting the inclusions along the columnar grain boundaries but also was not able to break the orientation of the inclusions in the radial direction because the area reduction during hot rolling was not high enough for that. The inclusion orientation of bars produced according to the former process was predominantly longitudinal, whereas, on the new process, the inclusions were also oriented on the radial direction reducing the material's ductility in the direction perpendicular to the coupler radius.*

Figure 14 - (a) General view of some connectors. Observe longitudinal cracks in two of them. (b) Sketch showing the orientation of the sulfide inclusions in both longitudinal and transversal directions of the continuous cast hot rolled steel bar. (c) Photomicrography showing the orientation of the inclusions in the radial direction observed on the transverse section of the coupler.



Source: Instituto de Pesquisas Tecnológicas (2009)

Other situations, in which shortcuts or changes on the traditional processes were responsible for failures, have been analyzed by IPT failure analysis team. Cases involving materials that had not had the microstructure properly homogenized due to a deficient combination between heat treatment and hot working are not uncommon. It is not uncommon either to have shafts and other moving parts to fracture due to fatigue initiated in internal flaws related to the continuous casting of plates and bars that suffered insufficient hot working after casting.

The classical processes to make plates, bars and forgings are highly energy consuming, because thick cast blocks and plates obtained from the steel plant require much hot working and reheating during rolling and forging operations. From more than half a century, classic ingot, billet and plate casting has been substituted by continuous casting which not only reduces the cost but also improves the productivity of steelmaking, demanding much less energy on the following processes of rolling and/or forging. Continuous casted plates and bars do not require much hot working to reach the desired size. However, the extensive hot working and reheating, required in the former process, can provide a better homogenizing of the material microstructure than that obtained from hot worked continuous casted plates and billets.

Because of the smaller reduction of thickness in rolling and forging of continuous casted plates and bars, the manufacturing of some products using this kind of material can become more complicated. The manufacturer buys steels that obey specifications established by standards long ago. However, the steels produced in the past were processed in such a way that some implicit properties, as bending or impact resistance provided by the former processes, were superior to the same properties in materials produced according the new continuous process. Since the new material attends the properties established by the standard (but not the implicit properties) the manufacturer that uses the steel will pay the onus of the innovation on the steelmaking, many times being led to change the manufacturing process or the material.

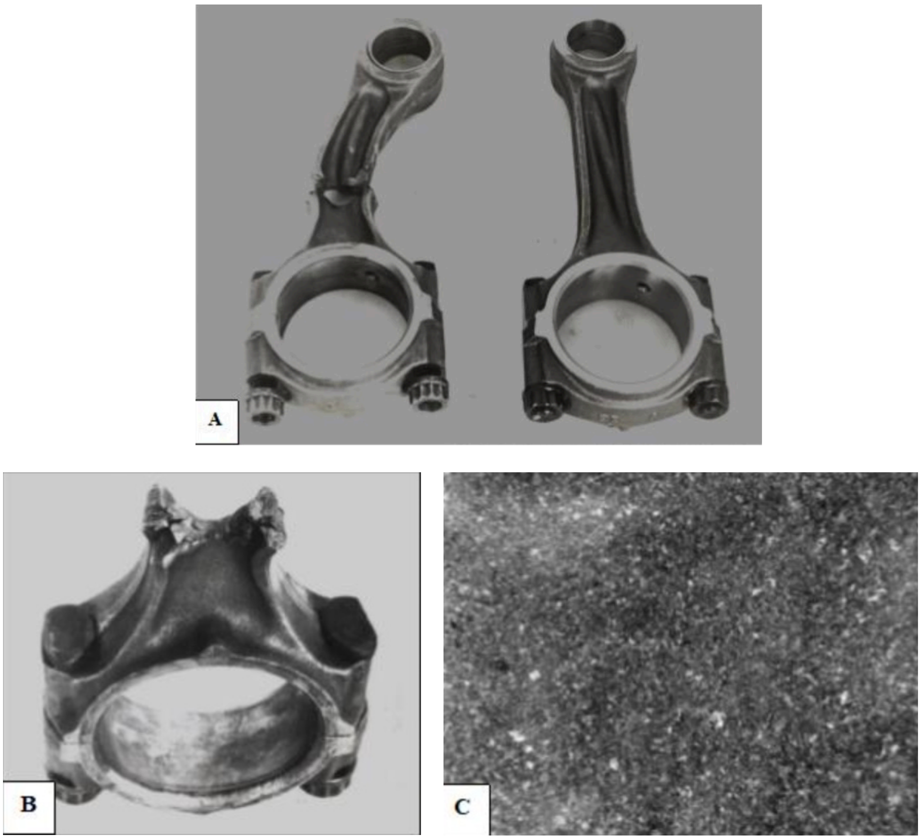
The conclusion is that the new processing techniques have been revolutionary and came to stay. However, for some applications, there is still a place for materials processed by the former way, mainly for those cases in which the materials cost is negligible when compared with the cost of a failure.

2.5 It could happen to you

Driving through flooded areas can bring a problem that many car drivers are not aware of. The best recommendation could be do not try to cross over a flooded area if you have a choice. Some people try to cross over flooded areas and water streams pushing the gas pedal to avoid the engine shut off. Many times, it works but if water level is high enough to reach the air admission, water will be sucked in, filling the engine cylinder, and causing a hydraulic block. What does it mean? When water is inside the cylinder, the piston, instead of compressing a mixture of fuel and air, it will compress liquid water. This process imposes severe dynamic compressive loading to the connecting rod leading it to buckle.

***Figure 15** (A) shows two connecting rods. On the left, one fractured after buckling due to a hydraulic block and, on the right, a new one (INSTITUTO DE PESQUISAS TECNOLÓGICAS, 1996). The fracture surface showed in **Figure 15** (B) was too damaged to be analyzed by SEM. The material presented a microstructure constituted of tempered martensite as can be observed in **Figure 15** (C) and hardness of 250 HB which was according to the specifications.*

Figure 15 – (A) Aspect of two pickup truck connecting rods. The one on the left fractured after buckling due to a hydraulic block and the one on the right was new. The fracture surfaces do not match perfectly because after the fracture the engine kept running for some time damaging them. (B) View of the fracture surface. (C) The microstructure of the material is tempered martensite.



Source: Instituto de Pesquisas Tecnológicas (1996)

To avoid hydraulic block, vehicles designed to cross over water streams (normally SUV's and trucks), besides four-wheel-drive, should have the air filter and the exit end of exhaust gases pipe positioned at the vehicle top level.

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