FRACTURE ANALYSIS OF MACHINE COMPONENTS USING FRACTOGRAPHY

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ABSTRACT

This paper provides an extensive study into the different types of material and component failures observed in industrial enterprises. Fractography is critical to failure analysis of metals and plastics. Fractography of plastics is a relatively new field with many similarities to metals. Failure modes common to both metals and plastics include ductile overload, brittle fracture, impact, and fatigue. Analogies can also be drawn between stress-corrosion cracking (SCC) of metals and stress cracking of polymers. Other metal/plastic failure analogies include corrosion/chemical aging, dealloying/ residual stress/frozen-in stress, and welds/knit lines. Stress raisers, microstructure, material defects, and thermomechanical history play important roles in both types of materials. The key fractographic features for metals and plastics.

INTRODUCTION

Fractography is critical to failure analysis of metals and plastics. Fractography of plastics is a relatively new field with many similarities to metals.Failure modes common to both metals and plastics include ductile overload, brittle fracture,impact, and fatigue. Analogies can also be drawn between stress-corrosion cracking (SCC) of metals and stress cracking of polymers. Other metal/plastic failure analogies include corrosion/chemical aging, dealloying/ residual stress/frozen-in stress, and welds/knit lines. Stress raisers, microstructure, material defects, and thermo mechanical history play important roles in both types of materials. The key fractographic features for metals and plastics.

HISTORICAL PERSPECTIVE

Plastics have been in existence for approximately 130 years. [1] John Hyatt patented nitrocellulose, the first commercial plastic, in 1869. However, full-scale development and use of plastics is only approximately 50 years old. In contrast, metals have been in use for hundreds of years. The application of engineering materials is unavoidably accompanied by the occurrence of failures, many of which have been catastrophic. The consequences of material failures, including deaths, financial losses, and legal ramifications, have encouraged the development of effective failure analysis methods. Although the cost of failure analysis may exceed the value of the part, the cost of service failures usually far exceeds the cost of failure analysis. Many of the techniques used over the years for the valuation of metals have been successfully applied to plastics, with only minor modifications. Fractography is arguably the most valuable tool available to the failure analyst. Fractography, a term coined in 1944 to describe the science of examining fracture surfaces, has actually been used for centuries as part of the field of metallurgy. Even before that, however, Stone Age man possessed a working knowledge of fracture. Archeological findings of lithic implements, weapons, and tools shaped from stone by controlled fracture indicate that prehistoric man knew how to select rocks with favorable fracture behavior, use thermal spalling to detach bedrock from the working core, and shape stone by pressure flaking. Fractography, as we know it today, developed in the 16th century as a quality-control practice employed for ferrous and nonferrous metalworking.

[2]De La Pirotechnia, published by Vannoccio Biringuccio in 1540, is one of the first documents to detail fractographic techniques. Invention of the optical microscope in 1600 provided a significant new tool for fractography, yet it was not used extensively by metallurgists until the eighteenth century.[3] In 1722, R.A.de Réaumur published a book with engravings that depicted macroscopic and microscopic fracture surfaces of iron and steel. Interestingly, the categories of macroscopic features developed by de Réaumur have remained essentially unchanged through the centuries.Partly due to the development of metallographic techniques for examining cross sections of metals, interesting microfractography waned during the nineteenth century. Metalworkers continued to use fractographic techniques for quality-assurance purposes,but, for the most part, researchers and publications ignored fractography. Several technological developments in the twentieth century revitalized interest in fractography.[4] Carl A. Zapffe developed and extensively used fractographic techniques to study the hydrogen embrittlement of steels. His work led to the discovery of techniques for photographing fracture surfaces at high magnifications. The first fractographs were published by Zapffe in 1943.An even more revolutionary development was the invention of the scanning electron microscope SEM).The first SEM appeared in 1943 .Unlike the transmission electron microscope, which was developed a few years earlier, it could be used for fracture surface examination. An SEM with a guaranteed resolution of approximately 500 Å became commercially available in 1965. Compared with the optical microscope, the SEM expands resolution by more than one order of magnitude and increases the depth of focus by more than two orders of magnitude. The tools for modern fractography were essentially in place before plastics achieved widespread use.

FAILURE ANALYSIS OVERVEIW:-

The general procedure for conducting a sound failure analysis is similar for metallic and nonmetallic materials. The steps include:

(1) information gathering;

(2) preliminary, visual examination;

(3) nondestructive testing;

(4) characterization of material properties through mechanical, Chemical and thermal testing;

(5) selection, preservation, and cleaning of fracture surfaces;

(6) macroscopic examination of fracture surfaces, secondary cracking, and surface condition;

(7) microscopic examination;

(8) selection, preparation, and examination of cross sections;

(9) identification of failure mechanisms;

(10) stress/fracture mechanics analysis;

(11) testing to simulate failure; and

(12) data review, formulation of conclusions, and reporting. Although the basic steps of failure analysis are nearly identical, some differences exist between metals and plastics. Nondestructive testing of metals includes magnetic-particle, eddy-current, and radiographic inspection methods that are not generally applicable to plastics, for obvious reasons. However, ultrasonic and acoustic emission techniques find applications for both materials. Similarly, different chemical test methods are necessary. Typical test methods for metals are optical emission spectrometry, inductively coupled plasma, and combustion. Fourier transform infrared spectroscopy is used extensively to identify plastics by molecular bonding, and thermal testing, differential scanning calorimetry, and thermo gravimetric analysis are also very important for polymer characterization. Energy-dispersive x-ray spectroscopy, used in conjunction with the SEM, is a very practical tool for elemental chemical analysis of both metals and plastics. Also noteworthy is that different chemical solutions are required for metals and plastics to clean and/or protect fracture surfaces and to etch cross sections to reveal microstructure.

CAUSES OF FAILURE:-

Of course, the primary objective of a materials failure analysis is to determine the root cause of failure. Whether dealing with metallic or nonmetallic materials, normally, the root cause can be assigned to one of four categories: design, manufacturing, service, or material. Often, several adverse conditions contribute to the part failure. Many of the potential root causes of failure are common to metallic and nonmetallic materials. Improper materials selection, overly high stresses, and stress concentrations are examples of design-related problems that can lead to premature failure. Materials selection must take into account environmental sensitivity- ties as well as requisite mechanical properties and welding/joining characteristics. Stress raisers are frequently a preferred site for fracture origin, particularly in fatigue. Stress raisers include thread roots (Fig.1), sharp radii of curvature, through holes, and surface discontinuities (e.g., gate marks in molded plastic parts).Similarly, many manufacturing and material problems found in metals also are observed or have a corollary in plastics. Weldments are a trouble-prone area for metals, as are weld lines or knit lines in molded plastics (Fig. 2) High residual stresses can result from metal forming, heat treatment, welding, and machining. Similarly, high frozen-in stresses in injection-molded plastic parts often contribute to failure. Porosity and voids are common to metal castings and plastic molded parts (Fig. 3).Pores and voids serve as stress raisers and reduce load-carrying capability. Other manufacturing- and material-related problems that may lead to failure include adverse thermo mechanical history, poor microstructure, material defects and contamination.

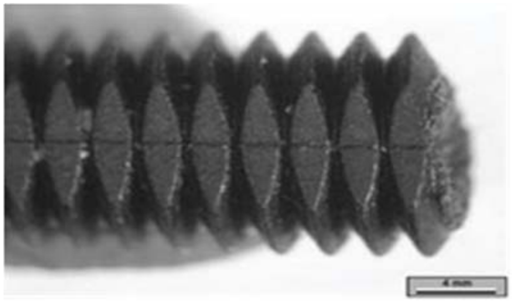

Fig. 1 Fracture of a glass-filled polyamide Cross section showing fracture along the threaded part due to stress concentration at the thread root. [1]

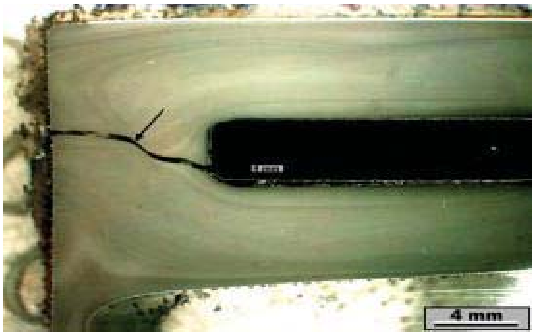

Fig.2 Cross section showing fracture along the knit line of a perfluoralkoxyethylene-lined impeller. [1]

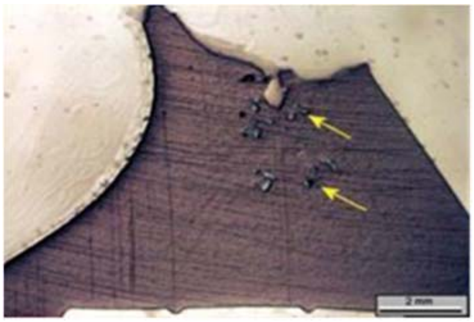

Fig. 3 Cross section of a polyacetal hinge that fractured (arrow) through an area of porosity. [I]

Environmental degradation is one of the most important service-related causes of failure for metals and plastics. Other degradation processes include excessive wear, impact, overloading, and electrical discharge.

FAILURE MECHANISM:-

Another key objective of failure analysis is to identify the failure mechanism(s). Once again, some failure modes are identical for metals and plastics. These modes include ductile overload, brittle fracture, impact, fatigue, wear, and erosion. Analogies also can be drawn between metals and plastics with regard to environmental degradation. Whereas metals corrode by an electrochemical process, plastics are vulnerable to chemical changes from aging or weathering. Stress-corrosion cracking (SCC), a specific form of metallic corrosion, is similar in many ways to stress cracking of plastics. Both result in brittle fracture due to the combined effects of tensile stress and a material-specific aggressive environment. Similarly, dealloying or selective leaching in metals (Fig. 4),the preferential removal of one element from an alloy by corrosion, is somewhat similar to scission of polymers (Fig. 5), a form of aging that can cause chemical changes by selectively cutting molecular bonds. Analogies can also be drawn between metals and another type of polymer: rubber. Internal hydrogen in steels can precipitate and cause hydrogen damage, which is frequently characterized by localized brittle areas of high reflectivity, known as flakes or fisheyes, on otherwise ductile fracture surfaces (Fig. 6). Similarly, explosive decompression in rubber O-rings produces fisheye-like ovular patterns on the fracture surfaces (Fig.7). Explosive decompression is the formation of small ruptures or embolisms when an elastomeric seal, saturated with high pressure gas, experiences an abrupt pressure reduction. This failure mechanism is analogous to the "bends" that afflict divers who surface too quickly.

FRACTOGRAPHY:-

When material failure involves actual breakage, fractography can be employed to identify the fracture origin , direction of crack propagation, failure mechanism, material defects, environmental interaction, and the nature of stresses. Some of the macroscopic and microscopic features employed by the failure analyst to evaluate fracture surfaces of metals and plastics are described subsequently. Note, however, that many of the fractographic features described forplastics are not observable for reinforced plastics and plastics containing high filler content.

MACROSCOPICALLY VISIBLE FRACTOGRAPHIC FEATURES:-

On a macroscopic scale, all fractures (metals and plastics) fall into one of two categories: ductile and brittle. Ductile fractures are characterized by material tearing and exhibit gross plastic deformation. Brittle fractures display little or no macroscopically visible plastic deformation and require less energy to form. Ductile fractures occur as the result of applied stresses exceeding the material yield or flow stress. Brittle fractures may occur at stress levels below the material yield stress. In practice, ductile fractures occur due to overloading or under designing and are rarely the subject of a failure analysis. However, the unexpected brittle failure of normally ductile materials is frequently the subject of a failure analysis. Many macroscopically visible fracto graphic features serve to identify the fracture origin(s) and direction of crack propagation. Fractographic features common to metals and plastics are radial marks and chevron patterns. Radial marks (Fig. 8) are lines on a fracture surface that radiate outward from the origin and are formed by the intersection of brittle fractures propagating at different levels. Chevron or herringbone patterns are actually radial marks resembling nested letter V"s and pointing toward the origin. Fatigue failures in metals display beach marks and ratchet marks that serve to identify the origin and the failure mode. Beach marks (Fig. 8) are macroscopically visible semielliptical lines running perpendicular to the overall direction of fatigue crack propagation and marking successive positions of the advancing crack front. Ratchet marks are macroscopically visible lines running parallel to the overall direction of crack propagation and formed by the intersection of fatigue cracks propagating from multiple origins. Brittle fractures in plastics also exhibit characteristic features, several of which are macroscopically visible (Fig. 9). These features may include a mirror zone at the origin, a mist region, and rib marks. The mirror zone is a flat, featureless region surrounding the origin and associated with the slow crack growth phase of fracture. The mist region is located immediately adjacent to the mirror zone and displays a misty appearance. This area is a transition zone from slow to fast crack growth. Rib marks are semielliptical lines resembling beach marks in metallic fatigue fractures.

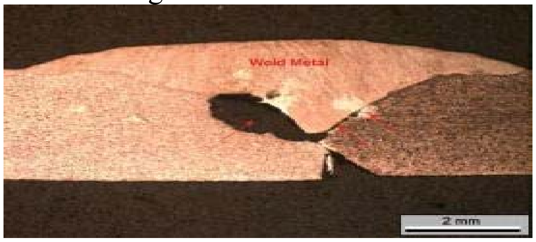

Fig. 4 Microbiologically induced corrosion of a 304 SST vessel weld, characterized by pitting and selective leaching (arrow). [2]

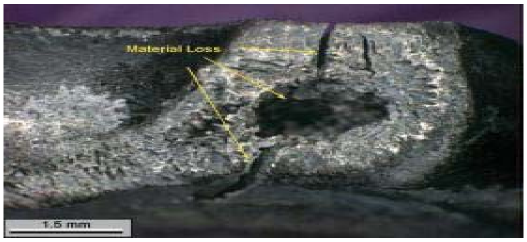

Fig. 5 Hollowing out of a polyacetal hinge due to acidcatalyzed Hydrolysis. [2]

Fig. 6 Hydrogen damage of induction-hardened steel piston rod displaying fisheyes. [2]

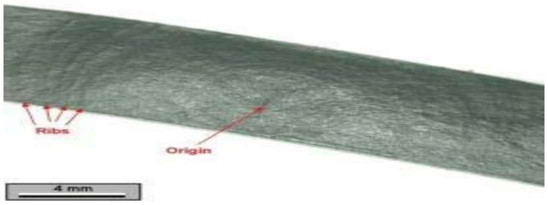

Fig. 7 Explosive decompression fracture of rubber O-ring, characterized by fisheye-like patterns. [2]

Fig. 8 Beach and radial marks visible on torsional fatigue fracture of a 6 in. Diameter shaft.. [2]

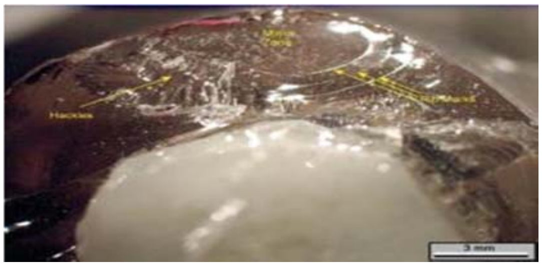

Fig. 9 Brittle fracture of an epoxy layer displaying a mirror zone, rib marks, and hackles. [2]

FRACTOGRAPHY OF METALS AND PLASTICS:-

It identifies the origin and the failure mode. Beach marks (Fig. 8) are macroscopically visible semielliptical lines running perpendicular to the overall direction of fatigue crack propagation and marking successive positions of the advancing crack front. Ratchet marks are macroscopically visible lines running parallel to the overall direction of crack propagation and formed by the intersection of fatigue cracks propagating from multiple origins. Brittle fractures in plastics also exhibit characteristic features, several of which are macroscopically visible (Fig 9). These features may include a mirror zone at the origin, a mist region, and rib marks. The mirror zone is a flat, featureless region surrounding the origin and associated with the slow crack growth phase of fracture. The mist region is located immediately adjacent to the mirror zone and displays a misty appearance. This area is a transition zone from slow to fast crack growth. Rib marks are semielliptical lines resembling beach marks in metallic fatigue fractures.

MICROSCOPICALLY VISIBLE FRACTOGRAPHIC FEATURES:-

On a microscopic scale, ductile fracture in metals (Fig. 10) displays a dimpled surface appearance created by microvoid coalescence. Ductile fracture in plastics (Fig. 11) is characterized by material stretching related to the fibrillar nature of the polymer response to stress. Although a part may fail in a brittle manner, ductile fracture morphology is frequently observed away from the origin. For example, the final fast fracture by ductile overload produces the shear lip in many metal failures, even when the crack originated and was propagated by SCC, fatigue, or hydrogen embrittlement processes. The extent of this overload region is an indication of the stress level. Generally, the larger the overload region, the higher the stress level on the failed component.Brittle fracture of metallic materials may result from numerous failure mechanisms, but there are only a few basic microfractographic features that clearly indicate the failure mechanism.These features are cleavage facets (Fig. 12), intergranular facets (Fig.13), and striations (Fig. 14). Cleavage facets form in body-centered cubic (bcc) and hexagonal close-packed metals when the crack path follows a well-defined transgranular crystallographic plane (e.g., the {100} planes in bcc metals). Cleavage is characteristic of transgranular brittle fracture. Intergranular fracture, recognizable by its “rock candy” appearance, occurs when the crack path follows grain boundaries. Intergranular fracture is typical of many forms of SCC, hydrogen embrittlement, and temper embrittled steel. Fatigue failures of many metals exhibit striations at high magnifications. (Normally, magnifications of 500 to 2,500× are required.) Striations are semielliptical lines on a fatigue fracture surface that emanate outward from the origin and mark the crack-front position with each successive stress cycle. The spacing of fatigue striations is usually very uniform and can be used to calculate the crack growth rate, if the cyclic stress frequency is known. Striations are discriminated from striation-like artifacts on the fracture surface in that true fatigue striations never cross or intersect one another. Plastics do not display cleavage and intergranular fracture. However, similar to metals, striations are found on fatigue fracture surfaces (Fig. 15, 16). Striations in plastics typically are observable at much lower magnifications (50 to 200×). However, local softening and melting due to hysteretic heating can obliterate fatigue striations in less rigid plastics. In addition to mirror zones, mist regions, and rib marks, which are normally visible without the aid of a microscope,

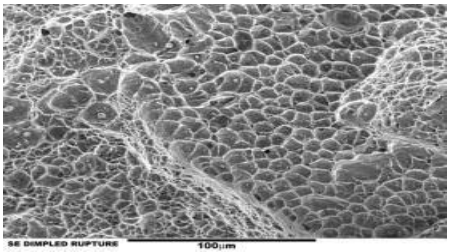

Fig. 10 Dimpled appearance typical of ductile fracture of metallic materials. [3]

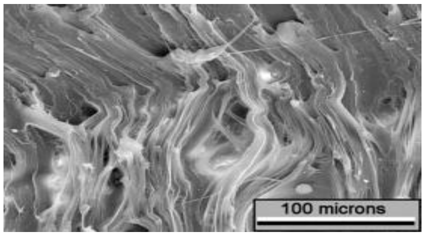

Fig. 11 Fracture of a polyethylene tensile-test specimen exhibiting material stretching. [3]

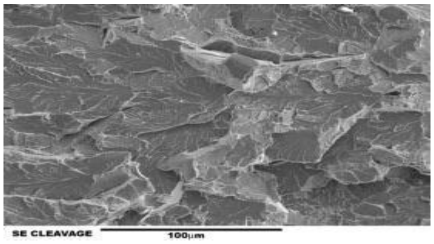

Fig. 12 Brittle fracture of an FC-0205 powder metal control rod displaying cleavage facets. [3]

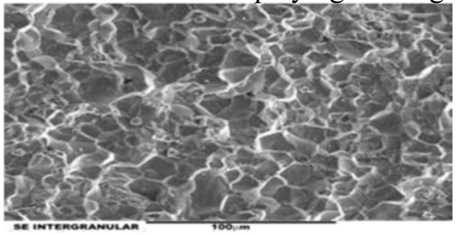

Fig. 13 Intergranular fracture of an embrittled cast steel pneumatic wrench. [3]

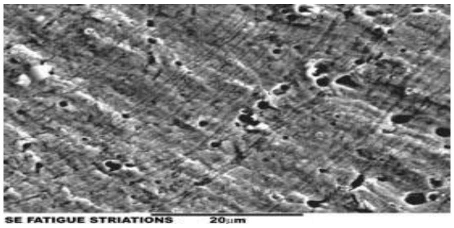

Fig. 14 Fatigue striations visible on type 302 stainless steel spring fracture. [3]

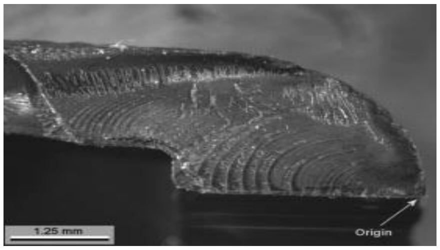

Fig. 15 Fatigue striations emanating from fracture origin of polycarbonate latch handle. [3]

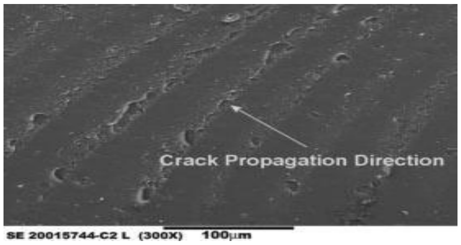

Fig. 16 SEM micrograph of fatigue striations shown in Fig.15. [4]

CONCLUSION

Fractographic techniques, developed and applied to metal failures for centuries, have been readily adapted to the fracture analysis of plastics since their emergence as a key engineering material over the last 50 years. However, more work remains to be done to advance fractography of plastics. One notable area for research is fracture analysis of composites, reinforced plastics, and plastics containing high filler content. Fractures of these materials too often are dismissed as inherently lacking meaningful fractographic features. Also this theory can be applied for the welded components so that the nature of failure can be determined so that their will be input data for the design team to make the necessary changes in the design, manufacturing processes which has to be carried out on the components.

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