

A CLASSIFICATION SCHEME FOR WEAR AND CORROSION

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ABSTRACT

Many components in a sugar factory require regular replacement. The need for replacement comes from excessive wear and/or corrosion that changes the dimensions of the component and reduces its ability to function as designed. On a component-by-component basis, efforts are being made to improve the life of components through the use of better materials or redesign to improve the operating environment. To aid in the process of identifying better materials, this paper presents a classification scheme for wear and corrosion failure modes. The classification scheme can be used to identify the type of wear or corrosion that is occurring so that materials suitable for withstanding the identified failure mode can be identified. Wear has been broadly classified into metal-to-metal wear, abrasive wear and fluid erosion. Corrosion has been broadly classified into corrosion producing material loss, corrosion producing property deterioration and mechanically assisted corrosion.

Key words: Wear, corrosion, material, selection

INTRODUCTION

Maintenance is a necessary investment that is required by sugar factories in order to maintain their reliability and efficiency. The need for maintenance arises mainly from the changes of dimensions of components, resulting from the wear and corrosion processes that occur. There is a continuing need to reduce the cost of sugar manufacturing to maintain competitiveness. The need to reduce maintenance costs, one of the major manufacturing costs, often leads to the search for different materials to improve the life of components. To aid in the selection of better materials, knowledge of the wear and corrosion failure modes is beneficial so that

replacement materials can be selected with better properties for reducing the impact of those failure modes. Here, we present a classification scheme for wear and corrosion failure modes that can be used to identify the type of wear or corrosion that is occurring so that materials suitable for withstanding the identified failure mode can be identified.

DEFINITION OF WEAR AND CORROSION

The selected definition of wear for this current work was stated by ASM (1992) as 'Damage to a solid surface, generally involving progressive loss of material that is due to relative motion between that surface and a contacting substance or substances.' Corrosion is

defined by ASM (1987) as 'the chemical or electrochemical interaction between a material, usually a metal, and its environment that produces a deterioration of the material and its properties.'

CLASSIFICATION OF WEAR AND CORROSION

Background

Currently, there are several published classification schemes for wear, but no equivalent published classification schemes for corrosion. The wear schemes available did not include corrosion aspects. In a sugar factory, there are many situations where wear and corrosion processes happen simultaneously and corrosion is a factor affecting the wear mode.

Classification of wear

The selected wear classification scheme was presented by Gates and Gore (1995), who broke wear down into three broad categories: metal -to-metal wear, abrasive wear and fluid erosion. Wear was then classified by wear modes, which were characterised by the combination of situation and manifestation to provide

recognisable wear types. Attached to each mode was a list of the wear mechanisms that were typically found to operate for that situation from past experience and research. These wear mechanisms are the fundamental processes involved in the surface damage and material removal. An understanding of the particular wear mechanisms was regarded

as providing a useful guidance for wear mitigation initiatives. By identifying the wear mode, the probable wear mechanisms may be surmised without requiring microscopic investigations for each situation. We used the wear mode classification scheme of Gates and Gore as the basis for classification of wear in sugar factories (Table 1).

Table-1 **Classification of wear modes**

Category	Mode	Situation	Manifestation
Low wear rates and oxidised debris	Severe sliding wear	Metal to metal sliding	High wear rates and metallic debris
	Mild sliding wear	Metal to metal sliding	Low wear rates and oxidised debris
	Fretting wear	Metal to metal oscillation	Bed of oxide debris
	Rolling contact fatigue wear	Metal to metal rolling	Pitting after an initial period followed by spalling
	Solid body impact fatigue wear	Repeated impact	Spalling after an initial period
Abrasive wear	Gouging abrasion	Large particles and extreme stresses or impact	Deep grooves and gross deformation
	Grinding (high stress) abrasion	Stresses sufficient to fracture abrasive particles	High wear rates and visible scratches
	Low stress abrasion	Stresses insufficient to fracture abrasive particles	Low wear rates and fine scratches
Fluid erosion	Solid particle erosion	Particles in high velocity gas	Surface profile related to flow patterns
	Slurry erosion	Particles in high velocity liquid	Surface profile related to flow patterns
	Liquid flow erosion	Flowing liquid	Low wear rates and surface profile related to flow patterns
	Liquid droplet erosion	High velocity droplets or liquid entrained gas flow	Medium wear rate, pitting
	Cavitation erosion	Cavitation (bubble collapse)	High wear rates and pitting

Table-2 Aspects of the wear situation that define the wear mode

Aspect	Description
Operating surface(s)	The nature (eg. composition, hardness, surface finish etc) of the surface (or surfaces for metal to metal wear) that is being worn and so requires maintenance
Mating component	The nature of the mating component whose wear is either not directly related to the wear of the operating surface or whose wear is of no concern. The main function of the mating surface is to transfer load to the operating surface.
Process material / interfacial material	The nature of the material being processed that is causing the wear and/or the nature of lubricants or foreign matter between two mating surfaces.
Mechanical motion	The nature of the relative motion between surfaces and materials (e.g. sliding, rolling, oscillation, impact, flow).
Mechanical severity	The severity of the mechanical interaction (pressure, velocity, impact energy etc)
Environmental	Temperature and the nature and action of corrosive materials (e.g. pH, conductivity, chloride ion concentration).

Description

The nature (eg. composition, hardness, surface finish etc) of the surface (or surfaces for metal to metal wear) that is being worn and so requires maintenance. The nature of the mating component whose wear is either not directly related to the wear of the operating surface or whose wear is of no concern. The main function of the mating surface is to transfer load to the operating surface. The nature of the material being processed that is causing the wear and/or the nature of lubricants or foreign matter between two mating surfaces. The nature of the relative motion between surfaces and materials (e.g. sliding, rolling, oscillation, impact, flow). The severity of the mechanical interaction (pressure, velocity, impact energy etc). Temperature and the nature and action of corrosive materials (e.g. pH, conductivity, chloride ion concentration).

The various wear modes can be exacerbated by either simultaneous corrosion, or alternate corrosion and wear (e.g. corrosion during the maintenance season may contribute to material loss during the crushing season). The effect can be either additive (i.e. the total material loss is equal to the sum of the wear and corrosive losses) or synergistic (i.e. the total material loss is greater than the sum of the individual wear and corrosion losses).

Incorporating corrosion into the classification scheme. It was a challenge to incorporate corrosion into the overall classification scheme while keeping the scheme relatively simple. We solved this by incorporating corrosion effects into the wear situation as an environmental aspect (Table 2). Including the corrosion aspect in this manner removed the need for specific wear-corrosion wear modes and a corrosion mode can be added to the other wear modes that may be occurring

for a given situation as discussed below. From the definitions above, wear is the result of a particular process, while corrosion is a process that produces particular results. Hence, the two terms are not directly comparable. The results of corrosion are analogous to wear, while the mechanical processes producing wear are analogous to corrosion. From this perspective, corrosion is regarded as the equivalent of a mechanical process producing material loss or damage and, therefore, included as an aspect of the wear situation that brings an additional set of wear mechanisms into play. In the case where corrosion processes are the dominant cause of (or provide a significant contribution to) material loss or deterioration of material properties, it is appropriate to include the corrosion mode as a wear mode. The majority of pure corrosion problems in the sugar factory appear to relate to dew-point corrosion, notably in the boilers and

process equipment. Dew-point corrosion is simply the source of a corrosive liquid that may result in various forms of corrosion. It is not sufficient to be a corrosion mode in its own right. Of the various recognizable forms (or modes) of corrosion, the most applicable to a sugar factory were identified and can be defined by situation and manifestation as per the wear modes. The forms of corrosive attack resulting in material loss may be general uniform (e.g. on mild steel), galvanic (the more active of two joined different metals),

pitting (e.g. stainless steel in chloride containing solution), or crevice (in small local stagnant areas). The forms of attack resulting in degradation of material properties may include intergranular corrosion (e.g. sensitized stainless steels) and stress corrosion cracking (in stressed components in particular corrosive media). These forms are determined by the material type and condition as well as the configuration of the operating surface, the nature of the corrosive medium, and the state of stress. The adopted

classification of corrosion modes is given in Table 3. Corrosion producing material loss has been categorized as either dry or wet corrosion. Dry corrosion is defined by the absence of a liquid electrolyte. Wet corrosion is defined by the presence of a liquid electrolyte, generally aqueous in sugar factory corrosive situations. Mechanically assisted corrosion includes fretting, abrasion-corrosion, erosion-corrosion, but these have been accommodated in the wear modes already listed in Table 1.

Table-3 Classification of corrosion modes

Category	Mode	Situation	Manifestation
Dry corrosion	High temperature corrosion	Metal in presence of high temperature air or oxidising gas	Formation of metal oxide scales
Wet corrosion	Uniform corrosion	Metal in contact with corrosive medium	Progressive thinning of exposed surface
	Galvanic corrosion	Electrically connected dissimilar metals in corrosive medium	Preferential attack of most susceptible metal
	Pitting corrosion	Chloride solutions (and oxidising metal ions) on stainless steel particularly	Holes (generally small) in the metal
	Crevice corrosion	Crevice holding small volume of stagnant corrosive medium	Intense localised corrosion
Corrosion producing property deterioration	Intergranular corrosion	Grain boundary regions more reactive than grains	Loss of strength and/or loss of grains
	Stress corrosion cracking	Tensile stress and specific corrosive medium	Fine cracking over surface with otherwise little attack
Mechanically assisted corrosion	Corrosion fatigue	Cyclic stress and corrosive medium	Reduction in fatigue resistance

FACTORS AFFECTING WEAR AND WEAR MITIGATION

Metal-to-metal wear

Mild sliding wear involves low wear rates where the wear debris produced is a layer of oxide that separates the two metal surfaces. Severe sliding wear, in contrast, involves high wear rates where metal debris is formed. In the absence of a lubricant, the severity for severe sliding wear can be reduced using harder materials, using dissimilar materials, using reacted surface coatings and using more readily oxidisable coatings (Lansdown and Price 1986).

For hypo-eutectoid steels, a bulk hardness of 350-450 HV is necessary to support a generated oxide film and so maintain the mild sliding wear regime (hyper-eutectoid steels require a bulk hardness of 250 HV for the same). Hardness levels of 700 HV suppress severe wear entirely. To increase wear resistance of two dry rubbing steel surfaces, they should be heat-treated to at least 550 HV.

Carbon steels have a more heterogeneous structure than stainless steels and so are less prone to severe adhesive wear (note that adhesive wear is a particular mechanism that can occur during sliding wear that involves localised welding between the two surfaces; the terms galling and scuffing are related to adhesive wear but usage of the terms is

often inconsistent). Smoother finish is more important on the harder component in the mating pair.

Metals resisting oxidation are more prone to adhesive wear. Fretting is characterised by surface pitting and fine loose debris (both oxidised) with pits 0.1-2.5 mm in size that are rough and corroded. Fretting can initiate fatigue failure at loads below normal fatigue limits. Prevention requires the exclusion of the corrodent by use of paints, oils etc or the complete separation of surfaces by non-metallic materials. MoS₂ has applications for reducing fretting wear. Under highly loaded conditions, insufficient strength of the separating material may be an issue.

Abrasive wear

Abrasive wear involves material displacement due to hard particles or protuberances being forced against and moving along a surface. When the abrasive particle hardness is less than 1.2 times the material hardness, wear rates are low due to contact being essentially elastic (sometimes referred to as soft abrasion).

When abrasive particle hardness is greater than 1.2 times the material hardness then plastic deformation (scratching) can occur and a higher wear-rate regime is entered (hard abrasion). For silica abrasives (800-1000 HV), materials with a hardness level of less than 670-830 HV will undergo

wear in the higher wear-rate regime. When abrasive particle hardness is greater than 1.8 times material hardness then increasing abrasive particle hardness has no further effect on wear rate. Wear mechanisms in abrasive wear include ploughing and cutting, which are forms of plastic deformation, and fragmentation, which is a brittle failure mode resulting from local cracking (Hertzian fracture) around the wear groove (i.e. plastic scratching is first required from which cracks initiate).

For a given hardness level, the ploughing mechanism results in the least wear loss, the cutting mechanism (i.e. direct material removal) results in higher wear loss, and the fragmentation mechanism (material spalling) provides the highest wear loss (wear rates may be an order of magnitude higher than for plastic mechanisms). Due to abrasion causing strain hardening and, hence, an increase in surface hardness, better correlation is generally found for wear resistance with the hardness of a worn surface than the bulk hardness.

In addition, strengthening by particles (e.g. by precipitation hardening) is only effective at increasing abrasion resistance if an increased strength is obtained at high strains. Hence, increasing hardness by cold work or precipitation hardening gives negligible increase in abrasion resistance, even if

considerable increases in hardness are obtained.

Once the fragmentation mechanism is involved, the fracture toughness becomes a critical property. When the ratio of hardness to fracture toughness is low then the material is less susceptible to cracking on indentation. For wear dominated by plastic deformation processes, the wear rate is affected by the ratio of elastic modulus (E) to hardness (H) as it relates to the fraction of plastic groove volume removed as debris.

Low values of E/H favour cutting over ploughing. Wear of polymers correlates more closely with the inverse of the work of rupture (work of rupture is the product of tensile strength and elongation) than with hardness. For heat-treated steel, E remains essentially the same, while H increases leading to lower values of E/H and, hence, to favouring the cutting mechanism.

This characteristic means increases in hardness may not give corresponding increases in abrasion resistance. Alloy white irons fall in the range of predominantly cutting to 75% ploughing. Where there are sufficient primary carbides and severe abrasion conditions, then fragmentation can occur. If an abrasive particle is sufficiently hard enough to scratch a primary carbide then it can initiate Hertzian cracks leading to fragmentation. Dual-phase structures such as cemented

carbides and hypereutectic white irons can undergo other mechanisms such as selective removal of softer matrix followed by pull out or fracture of the less-supported / more-exposed harder phase.

For cemented carbides such as tungsten carbide-cobalt, relatively soft particles such as quartz (quartz is soft relative to many ceramics) cannot plastically scratch the composite material and so wear occurs by soft abrasion where cyclic normal and tangential forces are applied to the carbide grains causing small movements leading to binder extrusion. The binder is then worn by the quartz particles.

Carbide particles may then detach or crack.

Angular particles create more wear than rounded ones as they are more effective at cutting and indenting. Fixed or constrained particles will be more effective at cutting or ploughing than rolling particles. Lubrication lowers the friction between a particle and the surface and so leads to more cutting. In low stress (scratching) abrasion, which generally involves a high concentration of abrasive moving slowly (<10 m/s), the contact stress is provided by abrasive weight if sliding or falling. Increasing the density of an abrasive increases its contact stress and hence the wear rate.

Increasing the load likewise increases the contact stress and at, sufficient load, the wear mode changes from low

stress scratching abrasion to high-stress grinding abrasion where the abrasive particles are crushed between rigid surfaces.

Solid particle and slurry erosion

Erosive wear (involving solid particles) is due to particle deceleration. The dominant force on an erosive particle resulting in its deceleration is the contact force exerted by the impact surface (other forces include weight, drag and inter-particle forces). Particle velocity is a significant parameter affecting erosion rate. If particle hardness exceeds material hardness then wear rates show little variation between metals of same alloy family in spite of large hardness differences of the alloys.

When the metal alloy is harder than the particle then erosion rates may be reduced such as for abrasion. Plastic wear mechanisms during erosion include cutting and ploughing. Where there is an element of ploughing, extruded lips are formed which may be removed by subsequent impacts. At low impact angle and low velocity, erosion is similar to scratching abrasion and so the wear mitigation principles are similar (Lansdown and Price 1986). In general, the hardest possible material should be used. As velocity increases, a higher level of toughness may be required. For bends in slurry pipelines,

the erosion can be reduced by increasing the radius of curvature so that the local component of particle velocity normal to the pipe wall is less than the maximum particle velocity at which collisions remain elastic. For high-impact angle, wear occurs due to repeated deformation and wear mitigation is more complex. Hard materials may be suitable at low velocities (i.e. at low energy impacts where elastic collisions occur). Impact velocity required for purely elastic collisions rarely exceeds 10 m/s for conventional construction materials.

For soft rubber materials, the limiting impact velocity may be much larger due to the low elastic modulus. Wear rate increases as velocity and erodent quantities increase. Rubbers require a hardness sufficient to resist particle penetration but not so hard that it loses elastomeric properties. Hardness should be achieved through cross-linking rather than through fillers.

Erosion corrosion

Erosion-corrosion involves the simultaneous occurrence of erosion and corrosion processes resulting in an accelerated rate of material loss. From one perspective, erosion corrosion is mechanically assisted corrosion. From another perspective, erosion-corrosion (or corrosion-erosion) is chemically assisted erosion. A corroding

metal (such as carbon steel) may produce corrosion products that adhere to the metal surface and so reduce the corrosion rate by slowing down the movement of ions at the reacting metal surface (creating a concentration polarization effect).

Active metals that exhibit passivity, such as stainless steels, form a protective oxide layer and behave as if they are inert as long as the oxide layer is maintained (oxide layer completely excludes corrosive solution from metal surface). The stability of the protective films is affected by environmental conditions such as temperature, pH, solution chemistry etc. Erosion corrosion occurs when mechanical damage of protective films leaves fresh metal exposed to corrosive attack. The more adherent the protective film, the greater the mechanical force required to remove the films.

Factors resulting in increased mechanical damage include impingement angle, and increasing velocity, turbulence, entrained solids content, and erosive nature of entrained solids. Where corrosion is accelerated due to corrosion product removal, the use of a passivating material such as stainless steel may be a suitable solution. If the erosive environment is severe enough to remove the passive layer of a stainless steel type material then a more inherently corrosion resistant material could be

considered such as some copper or nickel alloys. The molybdenum in 316 makes it more resistant to erosion-corrosion, as does the addition of iron to cupronickel due to better film stability. Ni-Resist has much better erosion-corrosion resistance than cast iron. Solid-solution hardening is the best method for increasing hardness to combat erosion-corrosion such as with high-silicon (14.5%) iron (which unfortunately is brittle, has low strength, and is difficult to cast). Non-alloyed cast irons generally do not exhibit reasonable corrosion resistance when solution velocities exceed 3.7 m/s (ASM 1996).

CONCLUSIONS

The wear and corrosion classification scheme has proven to be a useful way of examining wear and corrosion situations. It provides a method to identify the wear and/or corrosion mode. Knowing the mode of failure is a first step towards selecting an alternative material with better resistance to that mode of failure.

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REFERENCES

1. ASM. 1987. ASM Handbook Volume 13: Corrosion. ASM International: Materials Park.
2. ASM. 1992. ASM Handbook Volume 18: Friction, lubrication and wear technology. ASM International: Materials Park.
3. ASM. 1996. ASM Speciality Handbook: Cast irons. ASM International: Materials Park.
4. Gates JD, Gore GJ. 1995. Wear of metals: philosophies, practicalities. Materials Forum 19: 53-89.
5. Lansdown AR, Price AL. 1986. Materials to resist wear- a guide to their selection and use. Pergamon Press: Oxford.