SOME THOUGHTS ON AVOIDING METALLURGICAL FAILURES

by

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ABSTRACT

Predicting potential problems that will ultimately lead to premature material related failures and implementing the necessary corrections during design, fabrication, and commissioning has long been recognized by some as the most cost effective means of improving equipment performance.

Unfortunately, the technology and experience that are needed to recognize problems and provide solutions can only be gained by being exposed to and analyzing prior deficiencies and failures. In short, "Information gained is directly proportional to equipment ruined." Examples of environment-material interaction, improper material selection, incorrect processing, design considerations, and improper installation/maintenance will all be examined as they relate to avoiding failures.

INTRODUCTION

In service failures of most equipment are, in the majority of instances, directly attributable to the failures of *people* and in most cases easily *preventable*, as demonstrated in Figure 1. Fundamental factors that lead to failures of mechanical equipment are:

- Inadequate Design
- Improper Selection of Materials
- Deficiencies in Material Processing
- Imperfections in the Materials
- Errors in Assembly
- Improper Service Conditions (Misuse) and Inadequate Maintenance

Potential problem or *what if* analysis is an ideal technique of questioning in preventing failures. It is well suited for either an overall review or a one-on-one analysis of potential problems. The knowledge gained from comprehensive analysis of field failure is the background (root cause) that enables an engineer to predict problems, establish inspection frequency, and correct component designs. The real purpose is to prevent unscheduled outages, therefore permitting the equipment to perform its intended function satisfactorily and reliable. The premise of any design should be to establish expected overall life and the run time between *normal* service. Once that has been determined, the level of individual component performance can be fixed. The total failure of a piece of equipment seldom if ever occurs. Its always a component part that malfunctions. In most cases, it is a physically small component such as a spring, key, cotter pin, set screw, relief valve, lube oil fitting, etc.

Figure 1. Mechanical Failure or Human Error?

DESIGN INADEQUACIES

Sharp corners or abnormal stress-raisers, inadequate fasteners, unforeseen conditions of service and inadequate stress analysis are all examples of poor design. Residual stresses from welding, cold forming, and other upsetting operations must always be incorporated in the design calculations. Flexural fatigue failures due to sharp fillet and sharp keyways are two of the most common errors. Failure to properly analyze for dynamic loads or turndown conditions can both result in degradation of major equipment. Relative movement between components result in fretting which can lead to fatigue. Thermal gradients and cyclic pressures are frequently overlooked. Fastener creep failures from operating in the plastic range are also not uncommon. Improper interference fits can result in lose components, while excessive interference causes yielding or tensile overload failure in the most sever cases. Designs that incorporate thermal heat treatment of heavy sections next to light sections promote either the formation of a wide range of hardness or extensive quench cracking.

IMPROPER SELECTION OF MATERIALS

Frequently, materials that are too low in alloy to achieve full hardening are selected to save a few cents per pound. Drastic quenching is required to overcome the mass effect in large sections. This can lead to very hard localized areas that have microfissures and can eventually fail in fatigue. Materials that cannot either resist the general environment or will fail catastrophically by environmentally induced cracking from brittle fracture are frequently chosen. Choice of the wrong bulk material or surface treatment method can promote premature wear failures. Electroplating of high strength low alloy steels can induce brittle fracture from hydrogen unless the parts are baked to accelerate hydrogen diffusion. Hot and cold finished steel materials must be selected with adequate allowance for straightness tolerance and excess metal removal to compensate for surface discontinuities and chemistry variations due to decarburization, as shown in Figure 2. The location of weldments may be critical to achieve integrity, accessibility, fatigue properties, and subsequent heat treating cycles.

Nominal Diameter of Hot Rolled Bar Inches	Machining Allowance on DIAMETER Inches	Minimum Stock Removal from SURFACE Inches
HOT ROLLED CARBON BARS*		
1 1/2 to 3 incl.	0.125	0.063
Over 3	0.250	0.125
HOT ROLLED ALLOY BARS*		
Up to 5/8 incl.	0.032	0.016
Over 5/8 to 7/8 incl.	0.042	0.021
Over 7/8 to 1 incl.	0.046	0.023
Over 1 to 1 1/8 incl.	0.050	0.025
Over 1 1/8 to 1 1/4 incl.	0.056	0.028
Over 1 1/4 to 1 3/8 incl.	0.060	0.030
Over 1 3/8 to 1 1/2 incl.	0.066	0.033
Over 1 1/2 to 2 incl.	0.084	0.042
Over 2 to 2 1/2 incl.	0.104	0.052
Over 2 1/2 to 3 1/2 incl.	0.144	0.072
Over 3 1/2 to 4 1/2 incl.	0.180	0.090
Over 4 1/2 to 5 1/2 incl.	0.220	0.110
Over 5 1/2 to 6 1/2 incl.	0.250	0.125
Over 6 1/2 to 8 1/4 incl.	0.310	0.155
Over 8 1/4 to 9 1/2 incl.	0.406	0.203
HOT ROLLED TOOL STEEL BARS**		
1/4 to 1/2 incl.	0.030	0.015
Over 1/2 to 1 incl.	0.060	0.030
Over 1 to 2 1/2 incl.	0.125	0.063
Over 2 1/2 to 5 incl.	0.250	0.125
Over 5	0.375	0.187

Nominal Diameter of Hot Rolled Bar Inches	Machining Allowance on DIAMETER Inches	Minimum Stock Removal from SURFACE Inches
HOT ROLLED ALLOY BARS Subject to magnetic particle (Magnaflux) inspection*		
Up to 1/2 incl.	.060	.030
Over 1/2 to 3/4 incl.	.090	.045
Over 3/4 to 1 incl.	.120	.060
Over 1 to 1 1/2 incl.	.150	.075
Over 1 1/2 to 2 incl.	.180	.090
Over 2 to 2 1/2 incl.	.250	.125
Over 2 1/2 to 3 1/2 incl.	.312	.156
Over 3 1/2 to 4 1/2 incl.	.375	.187
Over 4 1/2 to 6 incl.	.500	.250
COLD DRAWN ALLOY BARS Subject to magnetic particle (Magnaflux) inspection*		
Up to 7/16 incl.	.060	.030
Over 7/16 to 11/16 incl.	.090	.045
Over 11/16 to 15/16 incl.	.120	.060
Over 15/16 to 1 7/16 incl.	.150	.075
Over 1 7/16 to 1 15/16 incl.	.180	.090
Over 1 15/16 to 2 7/16 incl.	.250	.125
Over 2 7/16 to 3 3/8 incl.	.312	.156
Over 3 3/8 to 4 3/8 incl.	.375	.187

Figure 2. AISI Machining Allowances for Surface Discontinuities, Decarburization, and Straightness Tolerances in Hot and Cold Finished Products Make it Advisable to Specify Materials with Adequate Allowances for Finishing.

DEFICIENCIES IN MATERIAL PROCESSING

Processing and fabrication variations determine the metallurgical changes and flaws that will be introduced into the component or structure. As single flaws and groupings of discontinuities become large, they can reach critical size resulting in either fatigue neuclation or catastrophic brittle fracture. Improper heat treatment cycles result in quench cracks, decarburization, or soft and hard zones. Quenching of steels with rough surfaces and/or heavy oxide mill scale will increase the length of the vapor phase and reduce the chances of achieving the critical cooling rate. These will promote the phenomenon of "slack quenching," and result in a less than ideal microstructure and reduced toughness.

IMPERFECTIONS IN MATERIALS

All man-made metals and nonmetals contain discontinuities. If they were perfect, almost no one could afford to use these to fabricate routine equipment. A discontinuity is considered a flaw when it makes the material unacceptable for the intended purpose. NDT techniques such as magnetic particle, liquid penetrant, radiography, ultrasonic Eddy current, AE (if properly used) can detect, locate, and identify these conditions. Such discontinuities as forging/rolling laps are depicted in Figures 3, 4, 5, and 6. Casting shrinkage voids, hot tears, surface cracking,

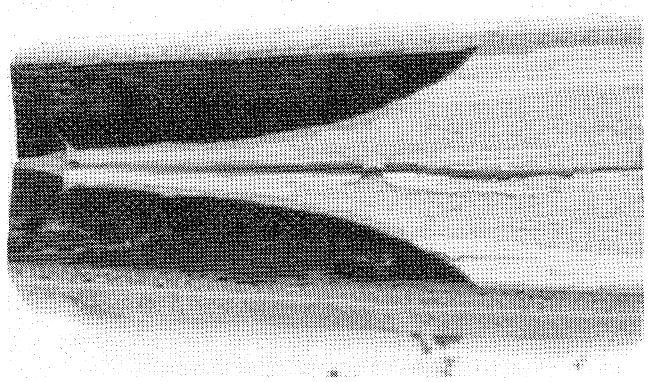

Figure 3. Macro Photograph of a Section of a Forgine/Rolling Lap.

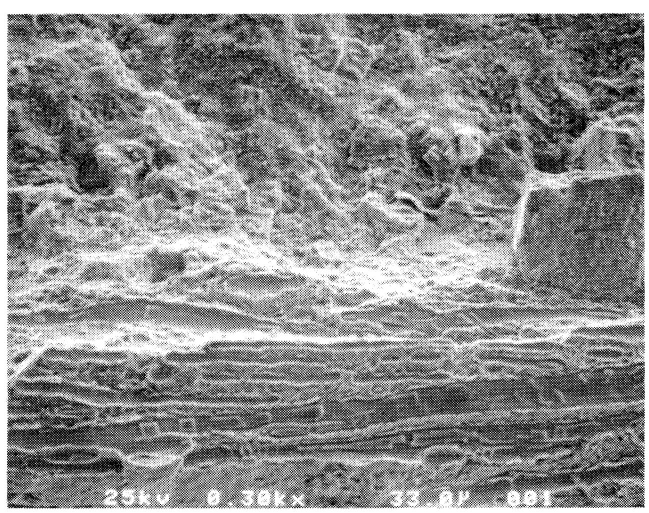

Figure 4. SEM Photomicrograph of the Lab Fracture/Surface Interface. Mag. 300X.

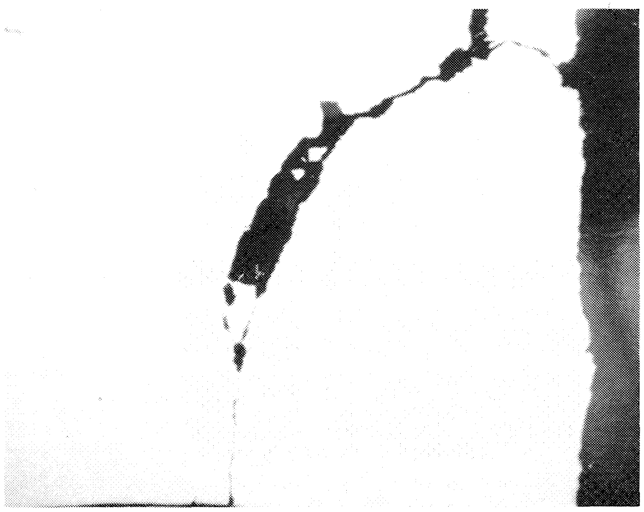

Figure 5. Unetched Section of the Rolling Lap in Figure 3. Mag. 75x.

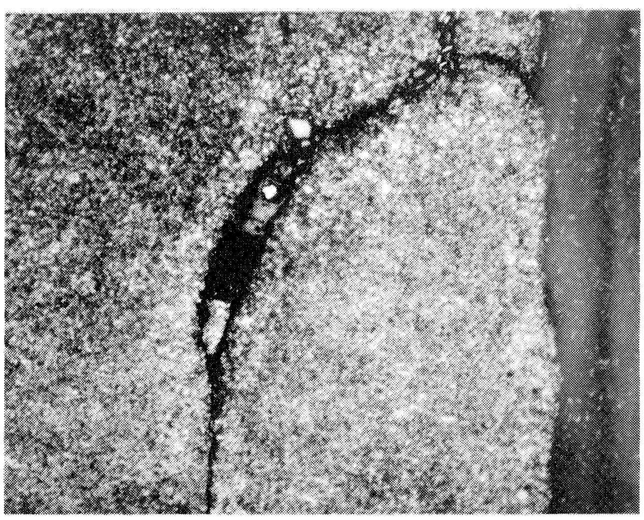

Figure 6. Etched Section Showing Decarburization ●f the Fracture Sides Indicating failure prior to thermal heat treatment. Mag. 75x.. Etchant—3 percent Nital.

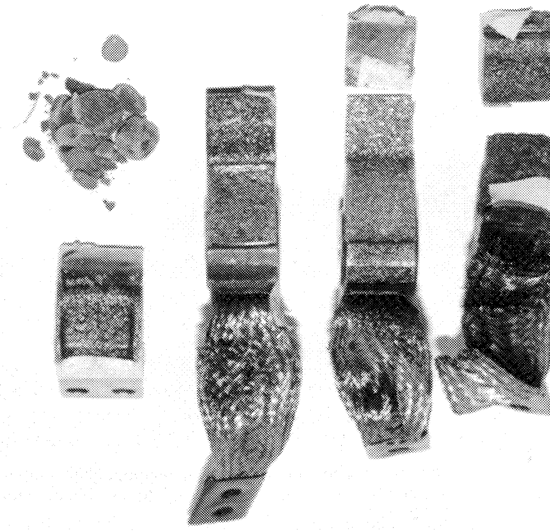

Figure 7. Failures of Transformer Contacts due to Poor Silver Brazing Resulted in Extensive Downtime to the Operating Unit.

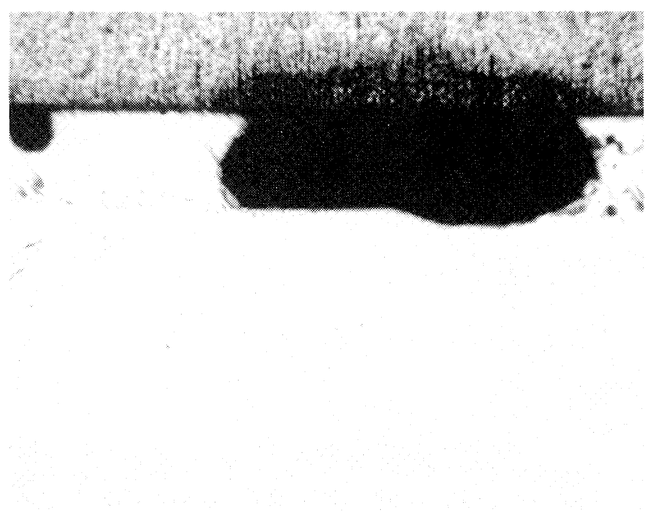

Figure 8. Poor Brazing of the Contacts to the Support Casting. Mag. 75x.

nonmetallic inclusions and laminations in wrought materials are all detectable. Specifications outlining the necessary techniques and go-nogo discontinuity sizes are available in the ASTM standards. Failure to adequately examine assembled components during preassembly (welding, brazing, etc.) can lead to catastrophic failure, as in Figures 7 and 8.

ERRORS IN ASSEMBLY

Misalignment, overtightening of threaded connections (Figure 9), loose keys, and improper bearing fits are the most common failures that result from assembly. Bearing fits generally lead to overheating and softening of materials, craze cracking of journals, and sometimes localized transformation of highly alloyed materials. Loose keys and misalignment almost always lead to bending or torsional fatigue failures. Overheating of threaded connections (Figures 10 and 11) promotes either an overload or the nucleation of a fatigue fracture. Insufficient tightening of fasteners can lead to fatiguing.

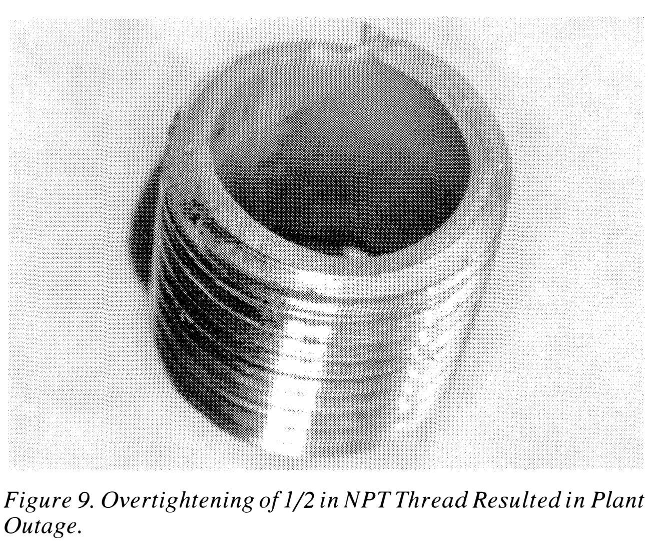

Figure 9. Overtightening of 1/2 in NPT Thread Resulted in Plant Outage.

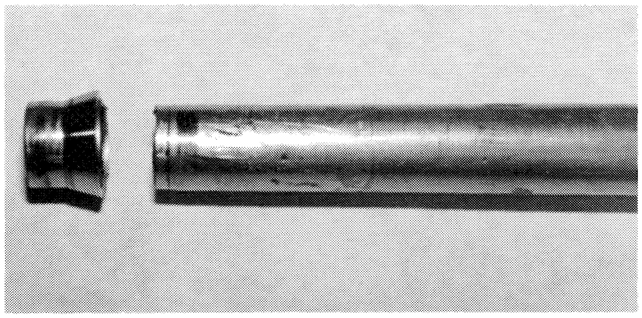

Figure 10. Compressor Lube Oil Line Failure Resulting in Plant Shutdown.

Figure 11. Lube Oil Line Failure due to Overtightening of 1in Tubing Connection. Scoring Initiated Fatigue Fracture.

IMPROPER SERVICE CONDITIONS AND INADEQUATE MAINTENANCE

Stress overloads (Figures 12, 13, and 14), excessive temperatures (hot or cold), inadequate lubrication, abnormal corrosive environments, excessive speed, shock, both thermal and mechanical, and excessive wear are all common misuse or misoperations that can promote premature component and material failures. Abnormal wear from erosion, galling, seizing, gouging, or cavitation are all too common. Loss of metal from corrosion including chemical attack, liquid metal corrosion, stress accelerated corrosion, corrosion fatigue, and metallurgical changes by corrosion such as dezincification or graphitization. Inadequate or improper maintenance such as poor lubrication, weld repairs, contamination, cold straightening without thermal stress relieving and routine wear compensation can lead to accelerated wear resulting in deformations that promote fatigue of rotating and stationary components.

Figure 12. Bending Fatigue Failure of a Pinion Gear Shaft Due to Improper Alignment.

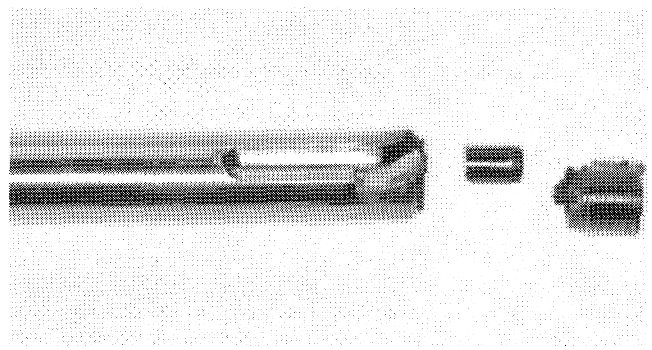

Figure 13. Insufficient Tightening of the End Fastener Resulted in a Loose Impeller in this Torsional Overload Failure.

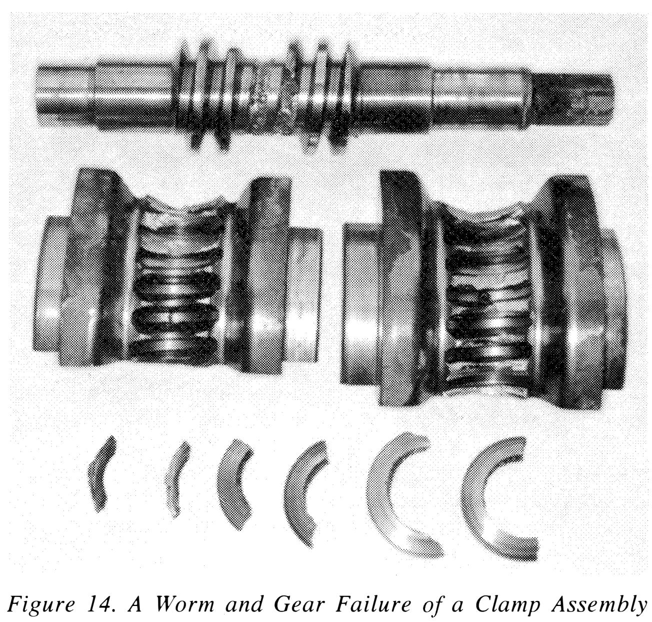

Figure 14. A Worm and Gear Failure of a Clamp Assembly Failure Due to Excessive Tightening/Overstress.

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