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How Management Decisions Make or Break Plant Uptime

Abstract

How Management Decisions Make of Break Plant Uptime: When you run machines above design rates that decision goes against all that we know about creating high plant uptime and outstanding equipment reliability—in fatigue situations 10% additional stress will cost you ten breakdowns.

The dominate factor in machine life and production plant uptime is the stress in your machines' working parts. The stress developed in a part's material of construction microstructure is directly linked to the force applied to it. It does not matter where the force comes from or why it is applied, once the stress in your parts go beyond their microstructure limits your machines fail. If you want to run at high production rates first ensure that your working parts cannot become overstressed.

Keywords: operating load, overload, production rate, deformation, component distortion

There is a passage in the first edition of the book 'Plant and Equipment Wellness' that says:

Retired Professor of Maintenance and Reliability, David Sherwin, tells this story in his reliability engineering seminars of the financial consequences for two organisations with different strategic views on equipment reliability. Some years ago a maritime operation brought three diesel engines for a new ship. At about the same time, in another part of the world, a railway brought three of the same model diesel engines for a new haulage locomotive. The respective engines went into service on the ship and the locomotive and no more was thought about either selection. Years later the opportunity arose to compare the costs of using the engines. The ship owners had three times less maintenance cost than the railway. The size of the discrepancy raised interest. An investigation was conducted to find why there was such a large maintenance cost difference on identical engines in comparable duty. The engines in both services ran for long periods under steady load, with occasional periods of heavier load when the ship ran faster 'under-steam' or the locomotive went up rises. In the end the difference came down to one factor. The shipping operation had made a strategic decision to de-rate all engines by 10% of nameplate capacity and never run them above 90% design rating. The railway ran their engines as 100% duty, thinking that they were designed for that duty, and so they should be worked at that duty. That single decision saved the shipping company 200% in maintenance costs. Such is the impact of small differences in stress on equipment parts.[1]

The extracted paragraph from Plant and Equipment Wellness explores the maintenance cost outcome of a boardroom decision to limit working loads in diesel engines to a maximum of 90% rated duty. It identifies the financial merit of the decision but it does not discuss its scientific and engineering merits. That is the purpose of this white paper—to identify the engineering proof for the monetary benefits that result from machine component stress reduction.

Production Limitations are a Part of the Design

Any time a machine operates its parts are put under stress and it is the stress in the machine's parts that will cause them to fail. Once a working part fails, so too does the machine; after which repairs must be made and paid. Somewhere in between disaster and dawdle you must decide where to run your machines. That decision has unsuspectingly huge cost implications for your company.

[1] Sondalini., Mike, *Plant and Equipment Wellness*, Engineers Media Australia, 2009, Pg 16

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Figure 1 shows two forms of stress vs. life performance curves for ferrous metals. The S-N Diagram is a typical fatigue curve for steel. Fatigue is caused by cycling loads. It is a confusing phenomena as the cycling does not require the load to go from positive to negative. Bolt fatigue occurs when the bolt is cycled under positive tensile load. The photograph of the bar shows the typical tell-tale 'beach marks' of a fatigue failure where each striation is the gradual growth of the initiation crack by an overload cycle. The Stress/Strain Diagram shows stress-strain behaviour curves for four types of ferrous metals from ductile iron to brittle alloy. These curves are made by putting a standard sample bar under increasing tensile load. Eventually the rising tension stretches the bar to yield by plastic deformation and ultimately separation. In every case, be it cyclic fatigue or extreme burden, stress in the excess eventually leads to material microstructure failure.

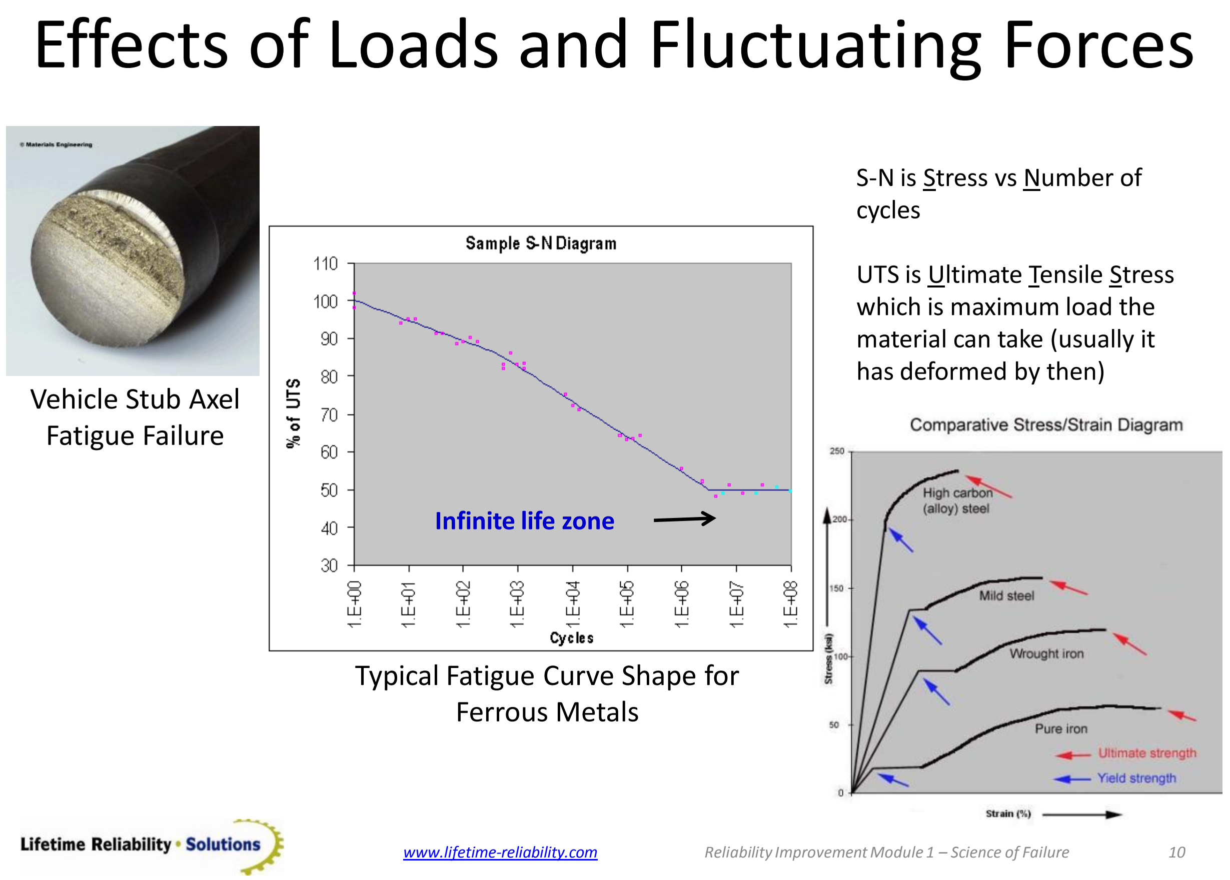

Figure 1 – Ferrous Metal Fatigue and Stress vs. Strain Curves

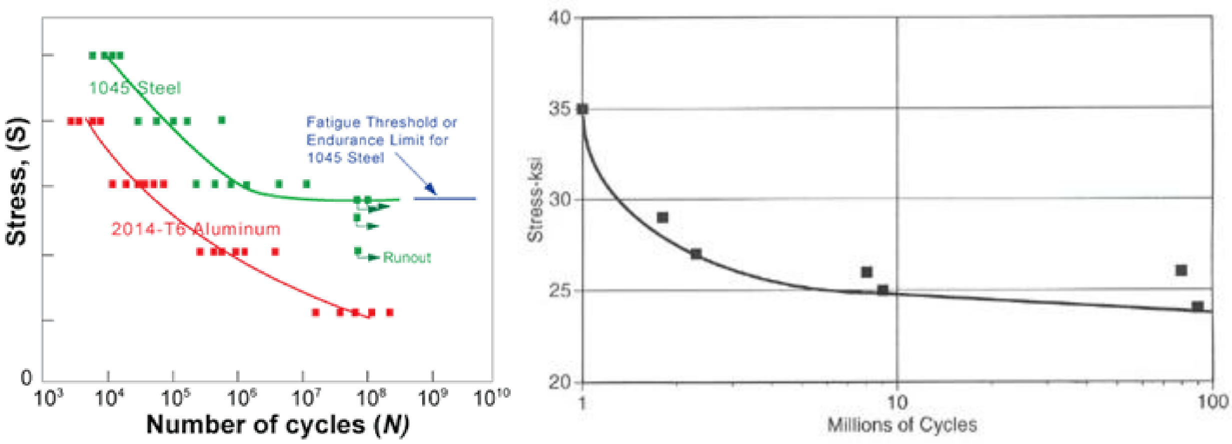

Figure 2 Fatigue Curves Showing Steel, Aluminium and Cartridge Brass (Right hand side)

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Figure 2 includes fatigue curves for an aluminium and a brass metal. The curves for those metals eventually go to failure. They do not have a threshold like steel where cyclic stress below about 50% UTS does not cause failure. Machine parts made of aluminium or brass fatigue with use at even low stress levels and they will need to be replaced in time before they fail. Fatigue life limits is why commercial aircraft frames made of aluminium are retired from service.

Excess stress of any type breaks your plant and equipment parts. But what does a 10% stress difference do to them? Under the purely tensile loads of our Ferrous Stress-Strain diagram a 10% increase does not destroy the item unless its stress level is already within 90% of the Yield Strength. Provided we keep stress within the straight portion of the curve the item will not fail. To prevent tensile failure in machine parts we design for maximum operating stresses that are in the lower 30% of the Stress-Strain line by using Factors-of-Safety on Yield of 3, 4 even 10 times. Though it is different again for high tensile bolts, which work in the upper half of the Stress-Strain line.

The dotted lines on vertical axis of Figure 3 are spaced 10% apart. This axis is a linear scale. At the point they cross the S-N Curve dotted lines drop to the horizontal axis. The horizontal axis is a $\log_{10}$ scale. At 80% UTS a sample piece is expected to last about 2,000 cycles before failing. At 70% UTS it should last about 20,000 cycles. At 60% UTS its life is about 250,000 cycles before failure. For the cyclic fatigue situations in Figure 3, 10% less stress produced upwards of ten times longer operating life. The same analysis done for aluminium and brass would also show how a small change in operating stress produces huge changes in operating lifetimes. That is why in Professor Sherwin's story the people that de-rated their diesel engines by 10% spent 200% less on repairs. In fatigue situations a 10% change in stress has big repercussions for your machine parts.

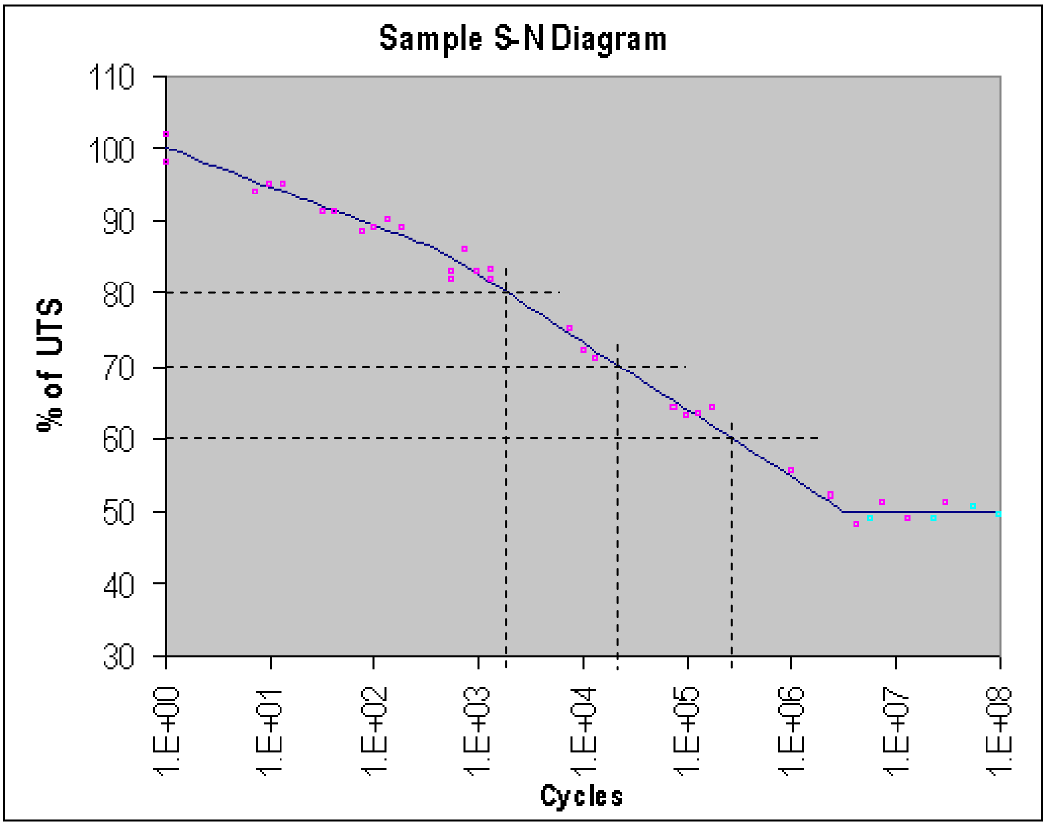

Figure 3 – Ferrous Metal Fatigue Stress vs. Life

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Figure 4 is meant to be a spoof. I composed it after reading Rod Bennett's article, 'Machines don't die, they're murdered.'[2] To be more accurate, it is the machine users and maintainers who murder them. They do not do it intentionally but, as Figure 4 highlights, the parts and machines end up broken.

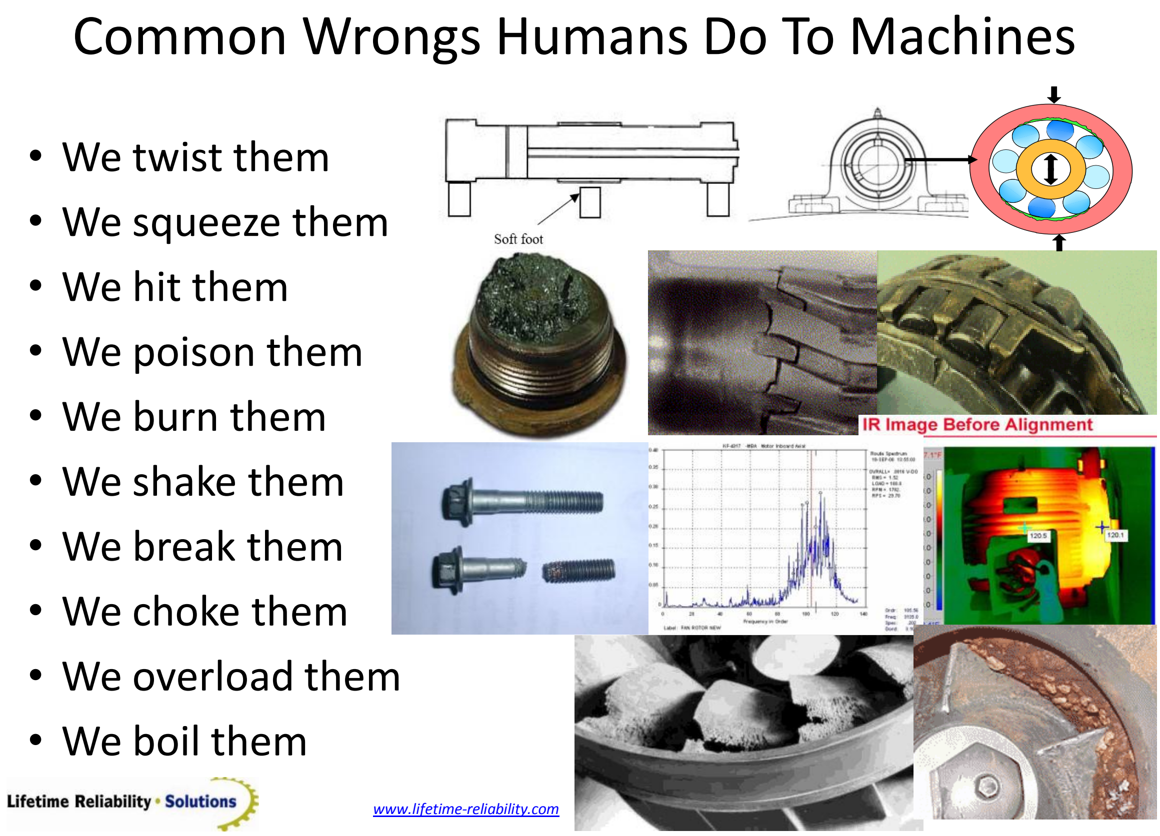

Figure 4 – 'Machines don't die, they're murdered.'

When machines are run their operating loads cycle. Machines create fatigue situations for their own parts. Though the machine designer limited the effects of fatigue by using Factors-of-Safety in choosing the materials of construction, they also presumed that the machine was precisely assembled and installed without extra pre-imposed stresses. Situation like the exaggerated shaft misalignment in Figure 5, from John Poitrowski's third edition of the Shaft Alignment Handbook, were definitely not what the pump designer expected. They did not design the pump to run with its shaft and bearings already heavily preloaded well up the Stress-Strain diagram line. When machines parts are badly deformed during installation the parts can be so severely stressed that they already carry a big percentage of their UTS before the machine even starts operation. We know that machine parts under high cyclic stress levels do not last long. Pre-stressing machine parts from bad installation will drastically shorten their life—remember that 10% excess stress can cost you ten breakdowns. When machine installers and maintainers put parts and machines into place deformed they guarantee the early death of their plant and equipment.

Machine parts do not care why the stress they suffer was imposed on them—they know not that a delivery was late and they were overloaded to make up time, or that the repairman did not have the tools nor the skills to do the job right—they simply fail when the stress gets excessive; regardless of its cause! Production Managers who approve overload levels of operation guarantee the early death of their machinery.

[2] Bennett., Rod, *Machines don't die, they're murdered*, National Condition Monitoring Forum Australia, August 2006

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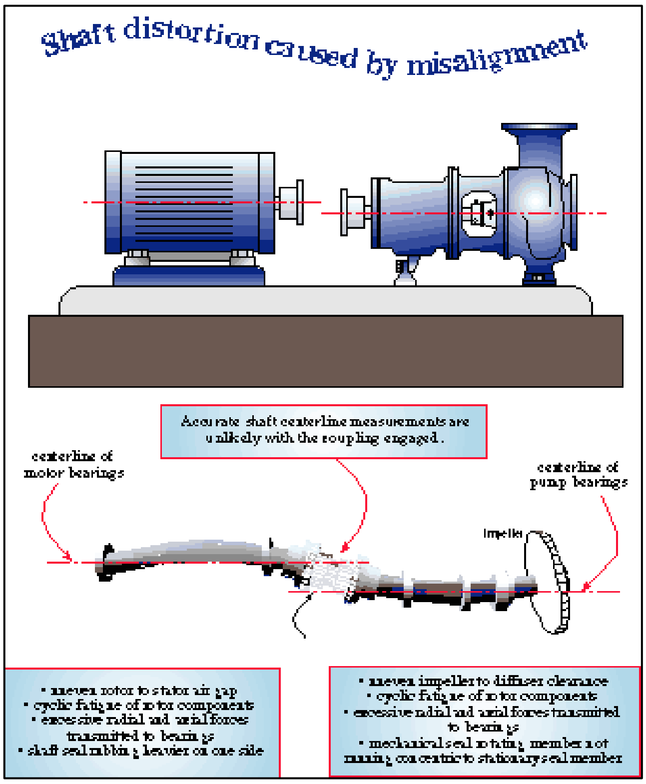

Figure 5 Stress from Shaft and Bearing Deformation

Engineering Limitations are a Part of the Design

The loads that machines work under produce forces and the forces cause the microstructure stresses which fail the machine's parts. Change the working loads and the forces change. Change the forces and the stresses change. We know the equations of these force-stress relationships. You will be surprised to see what a little change in force does to a part's stress.

The amount of stress at a particular point of a part's microstructure depends on the part's shape. To calculate the stress at a point in a part you must know its material properties and the distance the point is from where the force is applied. The maths and equations can get complicated for intricate shapes, but for a round bar the equation for the relationships between force and the resultant maximum stresses—axial, torsional, bending—are well documented.

Axial Stress = $F/\pi d^2$

Torsional Stress = $16[\, F.l/\pi d^3 \,]$

Bending Stress = $32[\, F.l/\pi d^3 \,]$

Where F is force, d is bar diameter, l is distance to the force from the point being analysed.

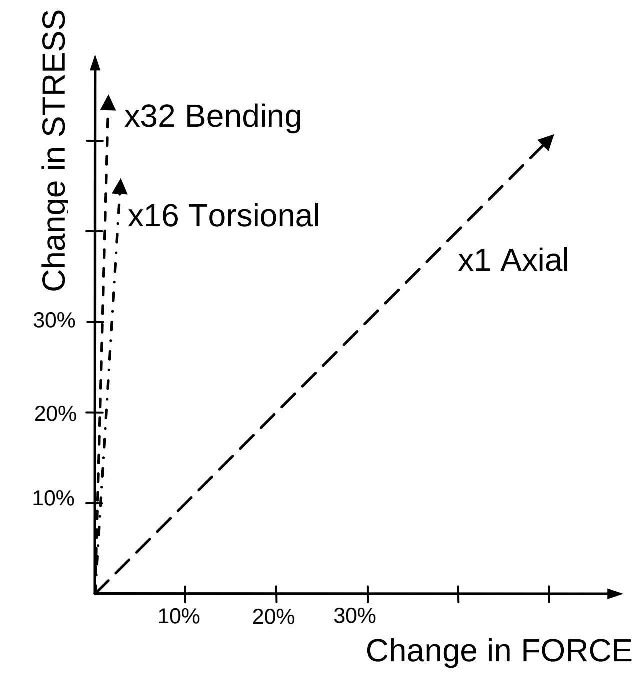

Figure 6 Force vs. Stress in Round Bars

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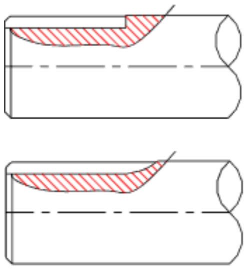
Figure 6 visually represents the change in stress for a change in applied force on a round bar. A 10% change in force causes the axial stress to increase an equal proportion, the torsional stress rises proportionally by sixteen (16) times and bending stress rises thirty two (32) times. All three stresses sum together at every point in the bar. Also added to those stresses is the extra stress due to the influence of shape changes, like the keyways and fillets shown in Figures 7 and 8 respectively, that concentrate stress in the microstructure.



Stress Concentration Factor K_f

	Bending	Torsion
Annealed	1,6	1,3
Quenched & Drawn	2,0	1,6
Annealed	1,3	1,3
Quenched & Drawn	1,6	1,6

Figure 7 Stress Concentration from Keyways

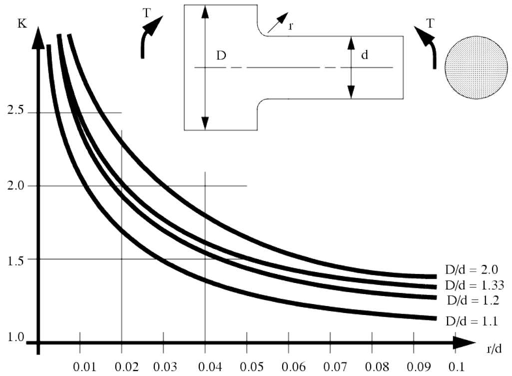


Figure 8 Stress Concentration from a Fillet

All stresses act concurrently throughout a part, so that the worst stress in an overloaded part may pass the material of construction Yield Stress and UTS. But there is more. Once the material microstructure cracks at the most stressed point, the stress concentration at the atomic crack edge hugely magnifies every stress by orders of magnitude, so that parts with stress fractures can start to break from fatigue even under normal operating loads.

All your machines have design limitations engineered into them. Run them with their parts distorted by overloads and/or deformed out of shape during installation and they will soon fail. Oh they will go when you press the start button; yes they will run—but not for long. Running pre-stressed machines at even only design duty, or intentionally running your plant at overload rates, are destructive maintenance and production decisions.

The metallurgical and engineering limits inherent in a machine always dominate all production requirements. If you want to run your machines at high production rates their working parts' microstructure must be in the least stress condition. Machine parts need to be installed deformation free, surfaces must be without stress raising damage, and you must never run them past design duty. In fact you would be wiser than most managers if you never ran them harder than 90% rated duty.

For your machinery parts, it is only the stresses within their microstructure that dictates whether or not they retain their integrity. They know not the reasons that overloaded them, nor what caused them to be deformed. Your opinions and beliefs carry no weight with them. They can only survive up to their stress limits, which once passed, destroys them. Then your production plant stops!

My best regards to you,

Mike Sondalini
Lifetime Reliability Solutions HQ
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