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SURFACE OPTIMISATION BY ENGINEERING THE STRESS AND ROUGHNESS

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ABSTRACT

Performance of turbine components can significantly be affected by surface/subsurface characteristics. Techniques applied today and being developed further entail introducing into a components surface a residual compressive stress of predictable magnitude and depth followed by superfinishing to improve the surface finish.

The effect will be to lower the mean stress which will increase component life and fatigue strength or enable higher loads through present designs; develop a damage tolerant layer capable of withstanding corrosion pitting or strike damage while in service and produce a final roughness capable of improving flow characteristics on turbine blades/buckets.

The processes to achieve the above include Controlled Shot Peening and Superfinishing. In combination, an optimised surface condition will result.

INTRODUCTION

Engineers from all fields are conscious of the applied stress during operation of any product. Time is spent calculating their effect and strain gauging operating parts to prove their calculations are correct or safe. However, components still fail at times irrespective of the efforts put in during these early stages of a product's development. Often this is because of a lack of understanding of how manufacturing stresses can affect the performance of a part. Safety factors are often applied to cover this grey area but, a better understanding of these manufacturing or residual stresses, their effect and how to influence or control them can greatly affect component performance and reduce costs.

Fatigue is often linked to surface finish and it is generally assumed that a finer finish will give better fatigue results.

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This may not be the case and care must be taken with the selection of any manufacturing process and the specifications of how each should be performed. However in situations where rolling or sliding contact and gas/fluid flow conditions are critical, reducing the surface finish and or changing the symmetry of the profile will lead to benefit.

MANUFACTURING STRESSES

All manufacturing processes, through the action of heat and/or cold work, will result in self stresses induced in a surface. These may be tensile or compressive; high or low in magnitude and quite shallow or of significant depth. In general the thermal manufacturing processes (welding, laser cutting, electric discharge machining, wire cutting) leave the surface with residual tensile stresses of high magnitude and a heat affected and recast layer. The depth will vary considerably with thermal manufacturing techniques but tensile stresses are normal. Chemical manufacturing processes tend to leave the surface of a part relatively smooth and stress free, but there may be some form of intergranular attack which, depending on the base material and the application may be detrimental.

The mechanical methods of manufacturing such as milling, turning, drilling and grinding equally vary the end result. This approach will vary the final stress but tend to be less of a concern than the thermal manufacturing techniques. However, the sharpness of the tool and speed of cutting are critical. Grinding is one of those processes whereby the surface may be left in a state of residual compression or residual tension of very high magnitude. Figure 1 shows the variation in residual stress profile that is feasible with three different types of grinding. [1]

That variation in stress level is plotted against fatigue strength and is shown in Figure 2, indicating a considerable variation in fatigue strength which designers and manufacturing engineers often are unaware of or ignore. [2]

Controlled Shot Peening on all of these processes will yield the surface in tension and superimpose a residual compressive stress. Even surfaces with a residual compressive stress will yield in tension and result in the typical stress induced by Shot Peening. Where deep self stresses exist from prior manufacturing processes, the Shot Peening parameters may have to be altered to ensure total relief of those prior stresses. However the influence of any detrimental manufacturing stresses will be reduced or eliminated with the result that the scatter phenomena of fatigue will be reduced and a general lift in fatigue strength noted.

FAILURE PROBLEMS

The technique of Controlled Shot Peening and Superfinishing are applicable to a range of failure problems such as Fatigue, Corrosion Fatigue, Stress Corrosion Cracking, Fretting, Fretting Fatigue, Galling, Wear, Cavitation Erosion, Surface Fatigue, Contact Fatigue and Spalling. Controlled Shot Peening and Superfinishing will, in combination, have an effect on residual stress, work hardening, surface roughness and grain size which will change the surface characteristics and correspondingly influence the failure problems mentioned.

Fatigue in metals is the result of repeated or cyclic loads at levels insufficient to cause large amounts of plastic deformation but sufficient to accumulate damage which may cause failure. One characteristic of fatigue is the random or unpredictable nature of its occurrence, hence the precautions adopted by designers concerned that a premature failure may result. This failure mechanism has been studied for nearly 150 years and today many sophisticated fatigue techniques exist using computers capable of complex mathematics but displayed on simplified graphics. It is therefore surprising that with this capability now available, where predictions on performance are possible for different geometric shapes and various applied stresses, that the influence of residual stress has been comparatively ignored. Figure 3 shows schematically the influence of residual stress on the mean stress and the potential benefit on extending life. [3] The general approach to residual stress in the majority of cases appears to have been to assume the worst and plan accordingly. While erring on the safe side, this approach ignores the considerable potential for fatigue life improvements of 10 to 30 times or fatigue strength improvements of 30%.

Stress Corrosion cracking (SCC) is a progressive fracture mechanism in metals that is caused by the simultaneous interaction of a corrodent and a sustained tensile stress. Structural failure due to SCC is often sudden and unpredictable, occurring after as little as a few hours of exposure, or after months or even years of satisfactory service. It is frequently encountered in the absence of any other obvious kinds of corrosive attack. Virtually all alloy systems are susceptible to SCC by a specific corrodent under a specific set of conditions.

The tensile stresses necessary for SCC are "static", and they may be residual and/or applied. Progressive cracking due to "cyclic" stresses in a corrosive environment is termed "corrosion-fatigue." The boundary between SCC and corrosion-fatigue is sometimes vague. Nevertheless, because the environment that cause them are not the same, the two are treated as separate and distinct metal failure mechanisms. Compressive residual stresses, such as those induced in the surface layers by Controlled Shot Peening, nevertheless, can be used to prevent or to delay both phenomena. The Stress Corrosion Triangle in Figure 4 shows how the removal of one part can influence the problem [4].

CONTROLLED SHOT PEENING

Controlled shot peening is a surface processing technique impinging the surface of a metal with spherical media to yield that surface in tension. The core of the material resists the stretching of the outer layers, resulting in a near surface residual compressive stress whose maximum value is approximately equal to 60% of the UTS of the base material in compression.

The relationship between residual stress and ultimate strength are shown on Figure 5. [5] The depth of residual compressive stress can be from a few microns to 2/3mm in depth.

The media used to conduct shot peening can be cast steel, stainless steel, ceramic or glass and vary in size from 50 micron to 6mm in diameter. Projecting velocities varying from gravity to 200 m/s.

Varying the peening parameters and therefore the kinetic energy transferred to the substrate will vary the residual stress profile shown in Figure 5.

The media required for processing must, as the ball pein hammer, be spherical in shape, ensuring all energy is dissipated yielding the base material with no cutting action as experienced during shot / grit blasting. New media is graded in both size and shape ensuring the starting point is known and thereafter continuously graded in operation to ensure the media shape is maintained. A loss of shape will result in loss of stress profile and thereby performance of the end product.

Coverage is critical to ensure that all of the original surface is obliterated. This ensures all prior detrimental stresses from whatever manufacturing techniques are removed and replaced by the compressive stress mentioned earlier. Coverage is checked by either a 10 X magnifying glass or preferably a fluorescent dye.

It is also important that wherever possible, the technique of shot peening is mechanised, ensuring that the stress profile required is repeated consistently from component to component.

Mechanisation has developed to such an extent that Computer Controlled Shot Peening machines are in use. The relative motions of the peening stream and the components are controlled, monitored and recorded in addition to the shot flow, pressure, media level, etc. The components are then released with a computer read out where the parameters during the processing are stated.

One specific application today uses a robotic manipulator to position the nozzle inside Inconel 600 steam generator tubing to retard stress corrosion cracking in the Nuclear Power Industry.

This work is performed on site and the closed loop shot peening system ensures accurate delivery and recovery of all media with all variables monitored and recorded confirming each tube has been treated properly.

SUPERFINISHING

Superfinishing is a technique of final machining in a controlled gentle manner to improve surface finish. The particular technique of superfinishing described in this Paper uses oxalic acids and vibrofinishing stones to preferentially remove surface asperities. The oxalic acids oxidise the surface which causes the asperities to be more susceptible to micro honing with the result that the most positive (peaks) surface areas are removed progressively. The vibrofinishing stones are selected to span machine lay and therefore cutting of the negative (valleys) surface areas are avoided. Consequently the symmetry of the profile can be altered producing a negative skew. This is ideal for contact or flow conditions where peaks are removed and valleys retained (the golf ball principle).

This technique has been applied to turbine blades/buckets coated or uncoated to improve surface finish. In situations where the metallic coatings produce finishes in the region of 10 microns Ra the preferred technique is to initially Shot Peen. This increases the density of the coating and reduces that initial roughness quickly. The intermediate finish could be in the region of 2.5/3.5 microns Ra. Better surface finish as could be achieved on some metallic coatings by secondary Shot Peening prior to the Superfinishing phase. The Superfinishing will subsequently reduce these finishes to 1.0/1.5 microns Ra. However, the final finish is completely dependant on the starting condition and the length of time the processing is conducted. The longer the time the greater the cost. In bearing or gear applications where the starting roughness is very low as shown in Table 1, the final roughness can be less than 0.05 microns Ra. It will be noted from Table 1 that Controlled Shot Peening onto as-ground EN 36 case carburised gear flanks, removed the directionality of the ground finish and produced a similar High Spot Count across or along the machine lay. This feature gives benefit on the mating surface of seals where leakage may have been experienced.

Trials on gear flanks to reduce surface pitting have increased product life by four fold. The symmetry of the roughness in this instance was 0.0 Rsk prior to superfinishing and -0.5 Rsk after. Rsk is the measure of the symmetry of the profile about the mean line and it will distinguish between asymmetrical profiles of the same Ra or Rt. A negative Rsk or skew has a comparatively flat profile above the mean line and a positive Rsk or skew has a peaked or sharp profile above the mean line. The roughness readings were 0.494 micron Ra (2.944 Rt) initially and 0.059 micron Ra (0.446 Rt) after superfinishing. However neither of these two types of measuring systems adequately indicate how a surface will respond in a contact situation. The negative Rsk is a preferred approach on any contact application such as gear flanks or bearings.

CONCLUSIONS

Engineering the surface stress and roughness may be considered as an additional cost. However in any situation where the total life cycle of the product is a concern, the costs of product failure and lost production must be part of the analysis. Consequently, taking care at the product design and production stage of the surface by developing a predictable residual compressive stress and superfinishing where flow or contact situations arise, will extend product life and reduce costs. This does not only apply at the initial stages of design and manufacture. In service, should premature failures arise, this approach can be implemented with the assistance/support of the initial design authority.

REFERENCES

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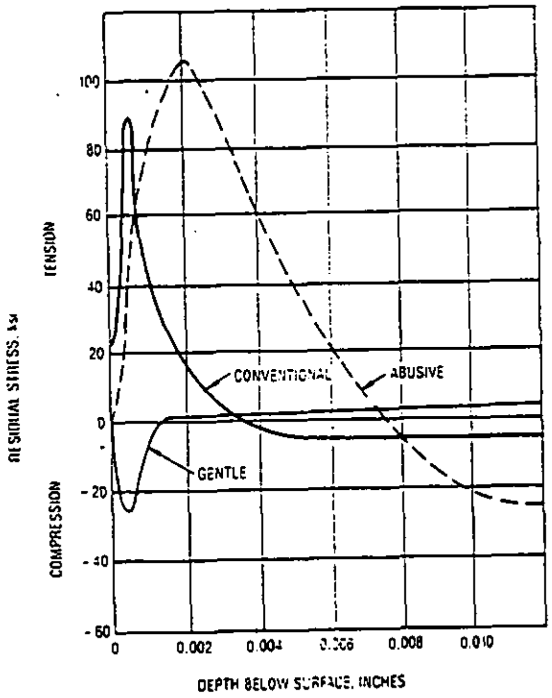


Figure 1 Residual Stress in AISI 4340 Steel (HRc50) after Surface Grinding

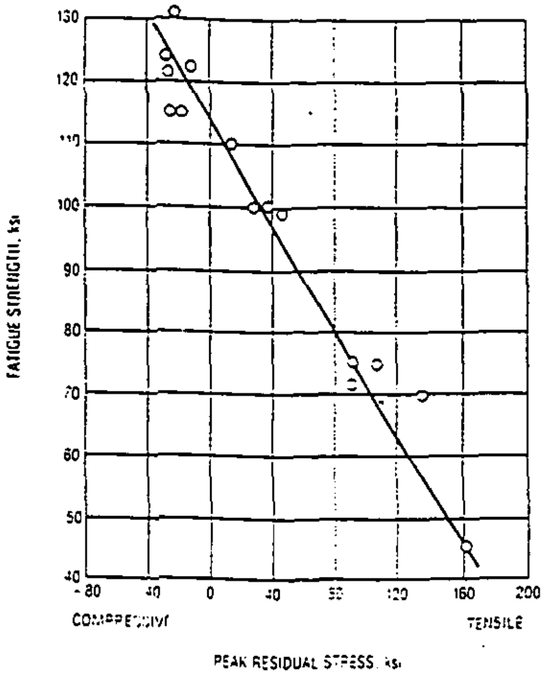


Figure 2 Fatigue Strength in Ground AISI 4340 (HRc50)

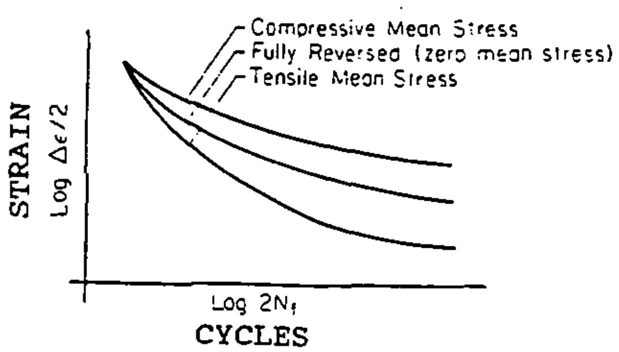


Figure 3 Effect of mean stress on strain-life curve

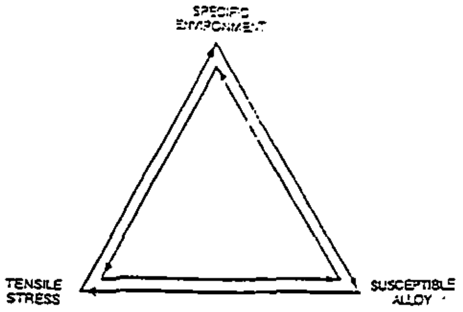
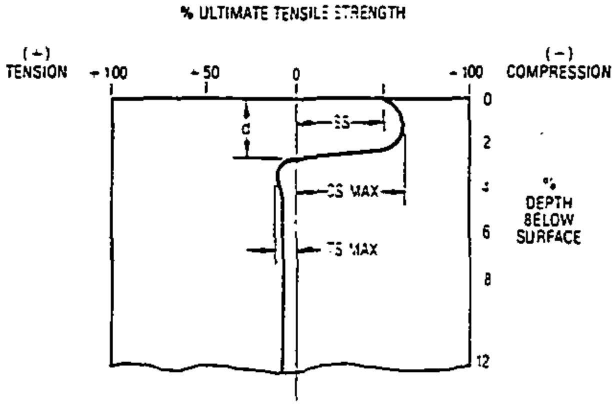


Figure 4 The Stress Corrosion Triangle



SS = SURFACE STRESS
CS Max = MAXIMUM COMPRESSIVE STRESS
d = DEPTH OF THE COMPRESSIVE STRESS
TS Max = MAXIMUM TENSILE STRESS

Figure 5 Example of Residual Stress Profile created by Shot Peening

Surface Condition	As Ground		Shot Peened		Shot Peened + Superfinished	
	Across Lay	Along Lay	Across Lay	Along Lay	Across Lay	Along Lay
Ra	0.083	0.084	0.233	0.248	0.044	0.043
Rt	1.079	0.619	1.99	1.933	0.277	0.389
Sm	24.931	185.243	80.44	31.448	80.413	64.955
HSC	155	22	50	49	48	55
Slope	0.1	0.06	0.23	0.23	0.06	0.07

Surface Readings In Microns

Table 1 Effect of Shot Peening and Superfinishing on EN36 Case Carburized Gear Flanks