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Superfinishing and shot peening of surfaces to optimise roughness and stress

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Abstract

Residual stress and surface roughness significantly affect component performance. For many years, Engineers have designated roughness constraints on drawings with little heed to residual stress. Fortunately this is changing as industries become aware of the significance of each and both are designated in critical applications. Superfinishing is developing as a post Shot Peening treatment in situations where metal to metal contact occurs, high temperature or fluid flow and/or optimum performance is required. Consequently the combination of residual stress and roughness control are essential on certain applications.

Introduction

Surface condition was not a critical feature to Engineers many years ago. In fact Shot Peening was an unpredictable black art of questionable benefit. This belief had some foundation many years ago, when occasionally, variable results were achieved. These variable results were partly due to ignorance of the Shot Peening process and partly a lack of understanding of surfaces, manufacturing techniques and their influence. Today, roughness and stress are better understood and as shot peening has developed from its shot blasting roots, the reason for this progression is becoming better appreciated. Shot Blasting is applied to achieve a surface effect and therefore, in most cases, any assessment was made subjectively by visually inspecting a surface. Shot Peening, and latterly Controlled Shot Peening, is practised by those interested in extending product life or uprating product

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performance. Any assessment should be made by inspecting the surface and sub surface for changes in stress and material structure. Unfortunately techniques are not available for indicating subsurface condition on all metals, therefore the application and control of shot peening becomes critical. Fortunately, Shot Peening equipment has developed, removing operator dependency, and with the ability to monitor parameters whilst the process is conducted, ensures greater repeatability of the technique.

Controlled Shot-Peening

Controlled Shot-Peening is the cold working of a surface with spherical particles, impinging at a predetermined velocity under controlled conditions. The surface yields but it is restrained by the substrate with the result that a residual compressive stress is induced as shown in Figure No. 1 [1]. This induced maximum compressive stress is approximately equal to 60% of the materials Ultimate Tensile Strength. The profile of the stress has been assessed as generating from a two fold mechanism. [2] The first, a plastic stretching of the surface due to tangential forces generated by multiple shot indentation, and second, a subsurface stress linked to the Hertzian pressure created by forces normal to the surface due to shot impingement.

Attempts at modelling the stress profile have been proposed [3] such that a prediction of the shot peening effect could be made. Many residual stress measurement techniques are available (X-ray and Neutron Diffraction, Centre Hole Drilling, bending deflection etc.) but none offer a non destructive, practical production method. Consequently the modelling technique, subsequently developed in conjunction with S.E.R.A.M. in France enables, with the input of shot peening parameters and material properties, a prediction of stress profile. A general guide to the depth and magnitude of stress is shown in Figure No 2 [1] but more detailed information is available via the prediction model.

Different media are used and these include cast and cut wire steel or stainless steel shot, glass and ceramic beads in size ranges from 50 to 3000 micron. Which to be used will depend on the geometry of the part; the material and its strain hardening rate; the application whether fatigue, stress corrosion cracking, galling, fretting, etc. and in service conditions. The geometry is critical in that access to the surface is essential but that does not exclude bores, even down to 2mm diameter.

However, in addition to inducing a residual compressive stress, several other changes occur. It is a cold working process therefore an increase in hardness will result; a change in magnitude and type of surface roughness; grain refinement and changes in martensite/austenite levels. These modifications to the surface have a number of advantages.

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Residual Compressive Stress

Residual stress and fatigue are directly related and can appear in testing as a wide scatter of data. This is demonstrated in Figure No. 3 [4] which shows the fatigue strength of Inconel 718 and its variability with machining whether using traditional or non-traditional manufacturing methods. It will be noted that it is not just the type of the machining process but whether done in a 'gentle' or 'abusive' manner. The scatter is seen as 15 to 42 Kg/mm^2 (ie 27 Kg/mm^2). The effect of Shot-Peening also shown on Figure No. 3, is to virtually negate the variations in manufacturing technique and leave a uniform residual compressive stress, with the scatter now 45 to 54 Kg/mm^2 (ie 9Kg/mm^2). Note also the increase in the lowest value of fatigue strength before and after Shot Peening, 15 and 45 Kg/mm^2 respectively (300%).

It is for these reasons that following processing of parts the first noticeable change is that the scatter is reduced, in addition to an increase in fatigue strength. However the benefit gained is sometimes difficult to quantify because of the unknown starting point, but a good guide is to assume a lift in fatigue strength of 25%. Fatigue life improvements then depend on type and magnitude of loading.

Manufacturing Techniques

Manufacturing techniques whether traditional or non-traditional vary the final stress pattern on the surface. 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 re-cast layer. The depth will vary considerably with thermal manufacturing techniques but tensile stresses are normal. [5] Chemical engineering techniques tend to leave the surface of a part relatively smooth and stress free but there may be some form of intergranular attack which, dependant 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. These techniques with the exception of grinding, are less of a concern than the thermal manufacturing methods. However the sharpness of the tool and speed of cutting are factors which effect the surface stress pattern. Figure No. 4 [6] shows recent work on lathe turned medium carbon steel 170HV and the residual stresses in the axial and peripheral direction. The axial stresses varied the most between +320MPa tensile to -180MPa compressive with the peripheral stresses more consistent, between +150 and +250MPa, but always tensile. Their effect on fatigue strength is shown in Figure No. 5. [6]

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 No. 6

[7]shows the variation in residual stress profile that is feasible with 3 different types of grinding. That variation in stress level is plotted against fatigue strength and is shown in Figure No. 3, indicating the considerable variation in fatigue strength which Designers and manufacturing Engineers often are unaware of or ignore.

Shot peening after all of these manufacturing techniques will yield the surface in tension and leave a residual compressive stress of the magnitude and depth previously indicated. Consequently the influence of these manufacturing stresses are reduced or negated resulting in a reduction in the scatter phenomena that fatigue normally exhibits, and an increase in fatigue strength.

Superfinishing

Superfinishing is a technique of final machining in a controlled gentle manner to reduce surface finish. The particular technique of superfinishing described 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. Ideal for contact conditions where peaks are removed and valleys retained.

The technique is not an adaption of electropolishing where all of the profile of the surface is de-plated. The technique of Superfinishing described has all of the surface oxidised but the honing action initially addresses peaks only which when partially removed, re-oxidises immediately making them more susceptible to abrasion once more.Tests have been completed investigating the oxidising effect to determine whether preferential grain boundary attack was experienced and whether deposits remained in the surface which could cause problems at a later date. EN 36 samples were case carburised and Superfinished and subsequently sectioned to 14,000X magnification, and no grain attack noted.[8]. Oxygen mapping was also conducted across an area processed three months previous to assess concentration or local oxidation problems and none were noted. Element checks were made using SEM equipment on surface peaks and valleys on the same sample again, and no traces were evident in the valley areas. The above is achieved because once adequate metal removal has been achieved, neutralising chemicals are added to prevent further oxidation.Once adequate checks of the technique were conducted, gears were processed to assess practical benefit. It was established that the process could be varied to suit the application. However the final finish is dependant on the starting condition and the time to process. Recent work on case carburised components in EN36, ground to simulate gear flanks produced the following results.

	As Ground		Shot Peened		SP + 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	1.990	1.933	0.277	0.389
Sm	23.931	185.243	80.44	81.448	80.413	64.965
HSC	155	22	52	49	48	55
Slope°	0.1	0.06	0.23	0.23	0.06	0.07

where

Ra = Arithmetic Mean of the departures of the roughness profile from the mean line.
Rt = Maximum peak to valley height of profile over assessment length.
Sm = Mean Spacing between profile peaks at mean line.
HSC = The High Spot Count is the number of complete profile peaks projecting above the mean line.
Slope° = Slope of profile throughout the assessment length.

and all dimensions are in microns.

The Process Controls

The success of inducing predictable self stresses as with other manufacturing processes or techniques is dependant on how the process is controlled. It is to be remembered that the aim is to generate residual compressive stresses of known and repeatable magnitude and depth. Consequently a knowledge of the important parameters and how they may affect the end result are critical. These parameters are as follows:

Media - The ball pein hammer is spherical and is familiar to most engineers. The shape was selected to stretch and yield the surface without cutting. For many years the ball pein hammer has been used to cold work a surface increasing its hardness and to stretch that surface enabling correct shape to be achieved. The media used in

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shot peening ideally should perform the same role. Where possible the media selected is spherical and all angular material rejected as a cutting action is to be avoided.

Coverage - Coverage is defined as the amount of surface that has been dimpled by the action of shot peening. Complete coverage is when the whole surface has overlapping dimples and none of the original surface remains, this is defined as 100% coverage. 200, 300 or 400% coverage are multiples of 100% coverage by factors of 2,3 or 4 times. Poor or partial coverage may result in areas of lower surface compressive stress, or at worst no effect at all, potentially leaving tensile self stresses from the prior manufacturing method.

Intensity - The intensity of Shot Peening is an indication of the kinetic energy (mass and particle velocity) transferred to the surface of the part and is demonstrated using the Almen Strip. J.O. Almen, who worked for General Motors in the 1920's developed a method of measuring, specifying and duplicating shot peening intensities. The Almen Strip works on a principle that if a flat piece of metal is clamped to a solid block and exposed to a degree of shot peening it will be curved upon removal from the block. The curvature will be convex on the peened side. The height of the curved arc, measured on a special gauge namely an Almen Gauge, serves as a measure of intensity. A variety of strips are available for different intensity ranges and the common three are manufactured from spring steel and are of varying thickness. Alternative strips of aluminium alloy and other materials, as the base alloy to be peened are now becoming available.

Mechanisation - To achieve predictable compressive self stresses from the shot peening technique it is essential to mechanise the process. Variations on how the process is controlled can result in variations in magnitude and depth of residual compressive stress. Consequently to achieve consistent processing it is necessary to mechanise the component and or the nozzles/wheels such that their relative motions can be repeated.

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

Designation - It is important that when specifying the process, all critical parameters are designated. An analogy is that many years ago designers used to specify 'heat treatment' or 'harden' on a drawing. Today they are well detailed in their requirements because it has been recognised that 'harden' is unspecific and a considerable fluctuation in performance would result. It is not uncommon to see shot peening specifications on a drawing simply state 'Shot Peen'. This, as in heat treatment, is totally unacceptable.

Conclusions

Residual or self stresses and roughness will vary significantly the performance of a component. Introducing a predictable residual compressive stress will improve component life and where metal to metal contact occurs, Superfinishing will reduce micro/macro pitting. A repeatable magnitude and depth of compressive stress can be achieved by Controlled Shot Peening a metal's surface and where necessary controlled micro honing of that surface will remove the asperities likely to puncture the lubricant film and cause premature failure.

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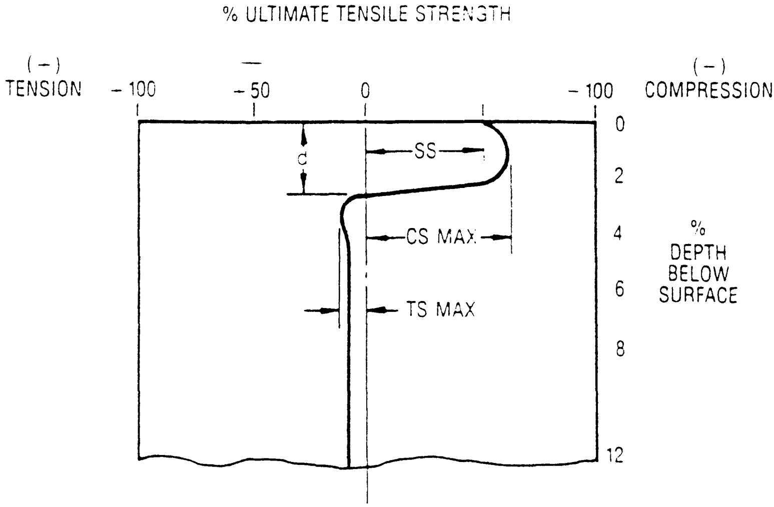

Figure 1: Example of Residual Stress Profile created by Shot Peening

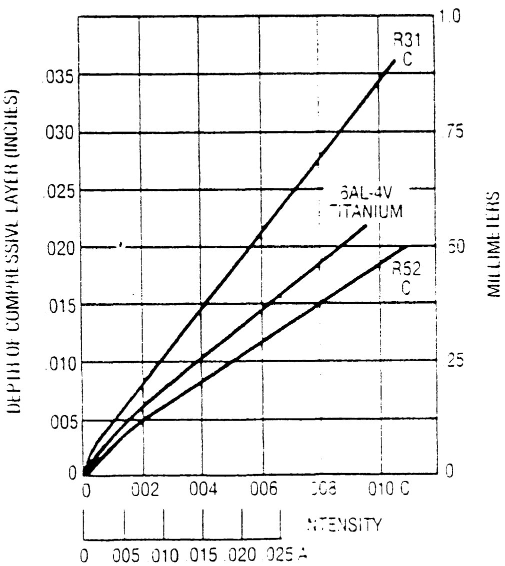

Figure 2: Depth of Compression vs Almen arc height

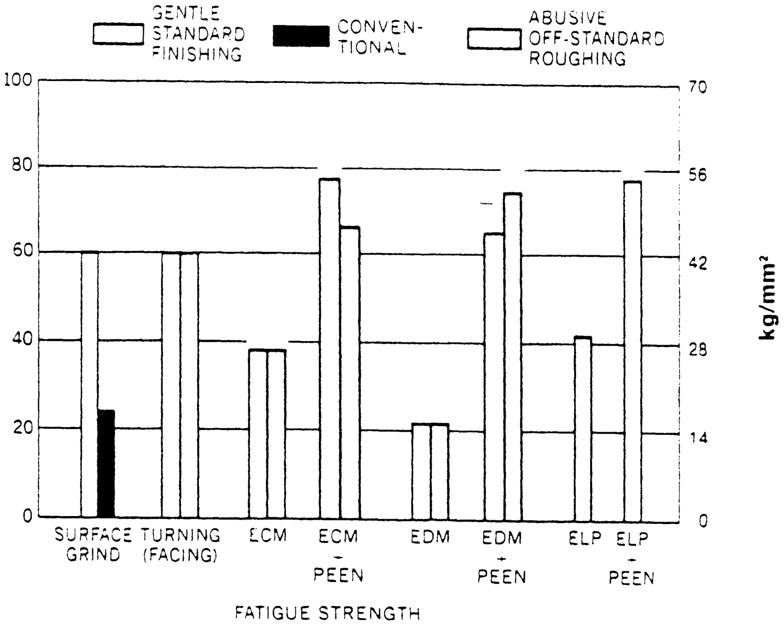

Figure 3. Summary of High Cycle Fatigue behaviour of Inconel 718, Solution treated and aged (Rc44)

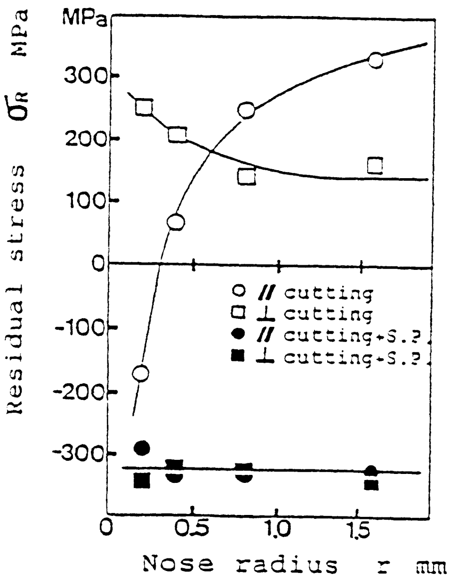

Figure 4: Surface residual stresses were varied with nose radius of cutting tool and were almost positive after machining but coincided after shot peening

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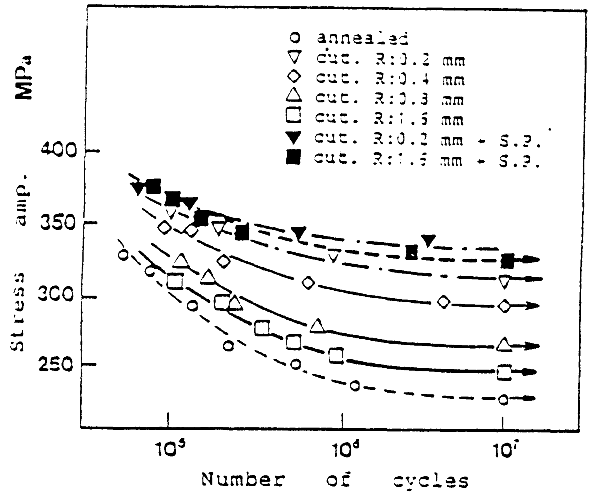

Figure 5: Fatigue strength increase with machining and shot peening

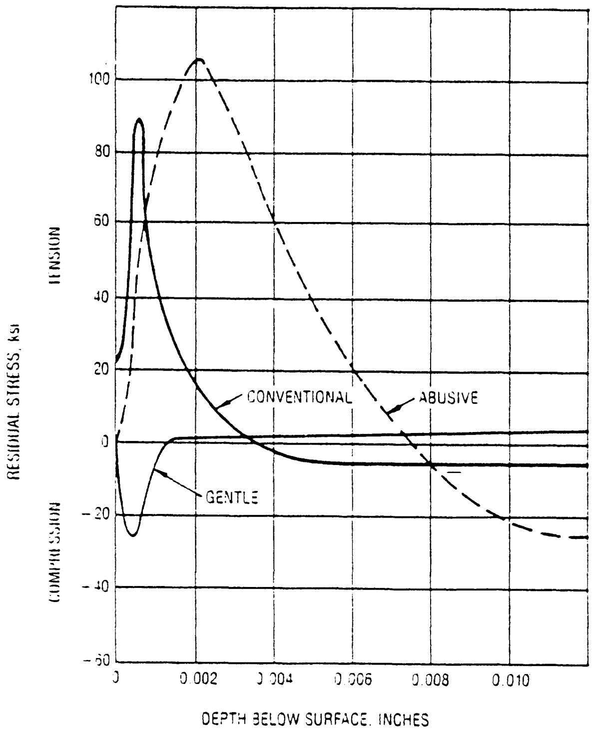

Figure 6: Residual stress in 4340 steel (HRC50) after surface grinding