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ABSTRACT

Many aerospace components undergo a finishing process during their manufacture. Such finishing processes include chromium, nickel, zinc and cadmium plating on steels; anodize on aluminum alloys; and various coatings on titanium and nickel base alloys. Certain of these finishing processes result in loss of fatigue strength of the part in question. Loss of fatigue strength caused by chromium and nickel plating amounting to 60% has been measured. Shot peening is frequently used on fatigue critical parts to regain fatigue properties which may have been lost due to a particular finishing operation.

Shot peening is a process which bombards the surface of a part with small spherical balls. The cold working effect of the peening balls leaves the surface of the part in a state of residual compressive stress. The beneficial compressive stresses induced by shot peening are effective in increasing fatigue properties of the component.

Data will be presented illustrating the beneficial effects of shot peening components which are to undergo finishing processing. Additional data will be presented regarding recommended shot peening processing techniques which will lead to optimum increases in fatigue characteristics of finished components.

THE SUBJECT OF SURFACE FINISHING is quite broad and covers a large number of processes. In today's operating environments, more and more components are asked to withstand higher loads, be lighter in weight, last longer and exhibit more consistency than ever imagined. In order to meet these ever increasing demands, many parts undergo finishing processing. Finishing processing can include the various coating processes as well as processes that yield their final surface condition due to metal removal. The intent of finishing processes is to improve the ability of the material to: withstand wear, resist high temperatures, lower surface roughness, create cosmetic appearances, remove surface contamination, create complex geometries - to name a few. In this paper the authors will break down the finishing processes into two groups: coating processes and material removal processes. The authors will relate the effects of many finishing processes on the high cycle fatigue strength of various metals.

For those processes where an HCF debit has been measured, data illustrating the use of shot peening to recover the above debits will be presented.

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COATINGS

Commonly used coating processes discussed in this paper include: 1) conversion coatings such as anodize and chromate; 2) plating such as chrome, nickel and electroless nickel and 3) flame spray coating such as plasma spray. Table I shows the effect of coating processes on the endurance limit, or high cycle fatigue strength, of various metals (7075T6 aluminum, 4340 and 4333 steels, 6Al-4V titanium). In all cases, these coatings lower fatigue strength from a 13.1% reduction for electroplated nickel to a 68.9% reduction for plasma sprayed titanium material.

Coating processes can be detrimental to fatigue properties due to the following conditions:

1) The introduction of residual tensile stress into the base metal surface.

2) Coatings are often porous or contain cracks which may propagate into the base metal.

3) Coatings, themselves, are often hard or brittle and susceptible to fatigue cracking.

4) Due to chemicals present during processing, the possibility of hydrogen embrittlement also exists.

Each of the coating processes shown in Table I produce one or more of the conditions above. Some processes produce all four.

METAL REMOVAL

While coating processes actually add material to the component, other finishing processes are advantageous because they remove material. These processes use chemical, electrical, mechanical, or a combination of these means, to remove metal from the component surface. The metal removal processes may be used because they: 1) economically remove exotic materials, 2) provide smooth surface finishes, 3) remove unwanted contamination or 4) bring a component to its final dimensions. Table II shows the fatigue debit, or benefit, that has been observed with commonly used metal removal processes. It is interesting to note that the chemically and/or electrically controlled processes tend to lower fatigue resistance where closely controlled mechanical processes actually are able to improve fatigue properties.

Chemical material removal processes can create surface roughening but may also cause intercrystalline corrosion attack, both of which are detrimental to fatigue resistance. There is also concern, during chemical processing, about hydrogen embrittlement. Electrical discharge machining (EDM) creates a surface recast layer which can be porous, brittle and notch sensitive. The loss in endurance limit due to chemical or electrical removal operations can range from 21% to 63%.

Beneficial mechanical removal processes cold work the material and induce beneficial compressive stresses into the surface. Increases in endurance limit due to metal removal processes shown in Table II range from 5% to 23%. In addition, mechanical processes are able to provide improved surface finishes. Table III shows the effect of surface finish on endurance limit of conventional surface ground 4340 steel and grit blasted titanium 6Al-4V. In each case increasing surface finish decreases endurance limit. It should be mentioned that in order to achieve increased fatigue resistance due to mechanical metal removal operations, the processing must be adequately controlled. If not controlled, detrimental results are possible.

SHOT PEENING

Controlled shot peening will improve fatigue resistance in components processed by the finishing techniques previously mentioned. Shot peening is a process by which one bombards the surface of a material with small spherical balls. Each ball acts as a tiny peening hammer leaving the surface with an indentation or dimple. In order for the dimple to be created, the outermost fibers of the surface must yield in tension. The fibers below do not. The fibers below surface act to restore the surface to its original condition. The action of these fibers trying to restore the surface induce into the material a residual compressive stress.

TABLE I

Coatings

Process	Base Material	Endurance Limit at 10^7 cycles KSI	Change Vs Uncoated Material %
Hard Anodize(1)*	7075T6	14.6	-40.0
Chromate(2)	7075T6	26.1	-14.3
Chrome Plate(3)	4340 steel 270 KSI	74.0	-20.4
Electroless Nickel (4)	Titanium 6-4	30.0	-50.0
Nickel Electroplate(5)	4333 steel 160 PSI	12.3**	-13.1
Plasma Spray Metco 450 (6)	Titanium 6-4	27.0	-68.9

* Numbers in parentheses designate references at end of paper.

** Fatigue Strength at 3×10^5 cycles

TABLE II

Metal Removal

Process	Base Material	Endurance Limit at 10^7 cycles KSI	Change Vs Uncoated Material %
ECM (8)	IN718 HRC 44	39.0	-35.0
EDM (8)	IN718 HRC 44	22.0	-63.3
Grinding (longitudinal) (8)	4340 steel HRC 50	102.0	+13.3
Grit Blasting(6)	Titanium 6-4	58.0	-33.3
Honing (5)	4333 steel 150 KSI	14.0*	+5.0
Pickling (9)	Magnesium AZ91	9.5	-21.0
Roller Burnishing(5)	4333 steel 160 KSI	17.1*	+22.6

*Fatigue Strength at 3 x 10^5 Cycles

TABLE III

Effect of Surface Finish

4340 (HRC50)
Longitudinal
Surface Grind (8)

Surface Finish AA	Endurance Limit 10^7 KSI
8	117
65	110
127	100

4340 (HRC50)
Transverse
Surface Grind (8)

Surface Limit AA	Endurance Limit 10^7 KSI
11	120
58	100
128	85

Titanium 6Al-4V
Grit Blasted (6)

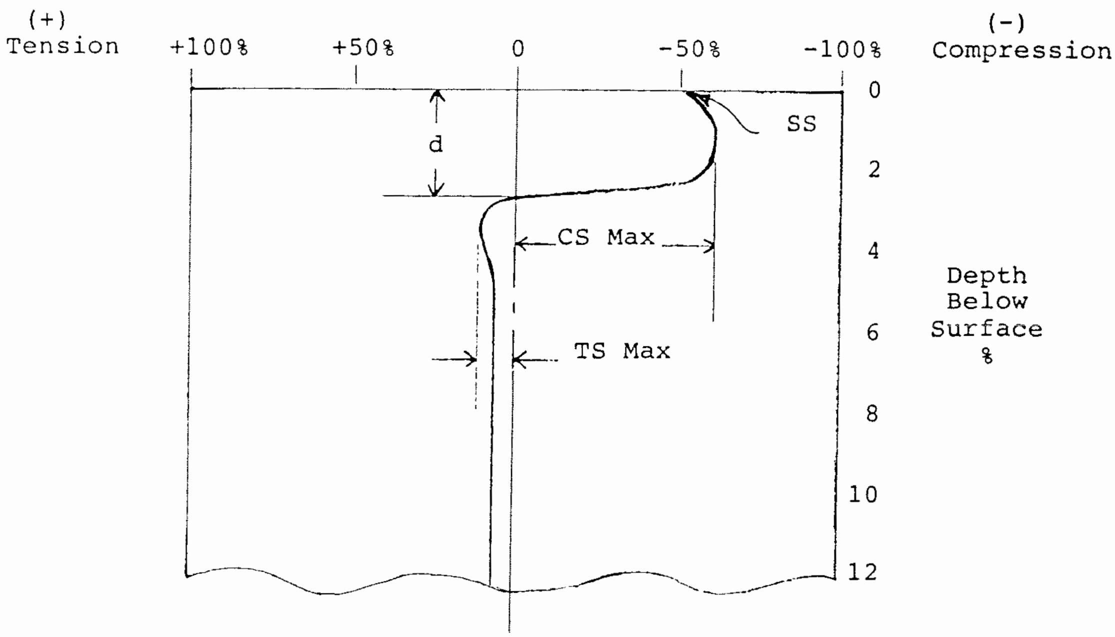
Surface Finish RMS	Endurance Limit 10^7 KSI
66	96
100	80
215	79

A typical profile of residual compressive stress induced by shot peening is illustrated in Figure 1. The profile has four basic characteristics:

Figure 1

RESIDUAL STRESS PROFILE

% Ultimate Tensile Strength



1) Stress at surface - SS.
2) Maximum value of compressive stress - CS max
3) Depth of compressive layer- d
4) Maximum value of tensile stress in core - TS max

The first characteristic seen would be the residual stress at surface (SS). The surface stress is somewhat lower than the maximum value of the compressive stress (CS max) which lies just below the surface of the material. The value of CS max is usually about 50% to 60% of the ultimate tensile strength (UTS) of the material being peened. The depth (d) of the compressive layer is the point at which the residual stress created by peening changes from compression to tension. The last characteristic of the residual stress induced by shot peening is the maximum value of tensile stress induced (TS max). Tensile stress is created to balance the residual compressive stress. In order for the component to be in equilibrium after peening, the compressive stress induced must be offset by an equal area of tensile stress. This offsetting tensile stress cannot be ignored. It should not be allowed to become sufficiently large to cause early internal fatigue failures.

It is the layer of residual compressive stress that provides the greatest benefit in improving fatigue resistance of parts by shot peening.

SHOT PEENING BENEFITS

Table IV illustrates benefits measured by shot peening <u>prior to</u> coating operations (hard anodize, chrome plate, nickel electroplate and plasma spray). The percent increase in endurance limit or fatigue strength ranges from a low of 53% to a high of 219% when compared to the as coated material. Shot peening is beneficial in that the layer of compressive stress induced: 1) negates the surface residual tensile stress induced during the coating operations, 2) prevents cracks in the coating from propagating into the base metal and 3) retards the migration of hydrogen into the base metal (10).

Controlled shot peening also provides improved fatigue resistance to components finished using metal removal techniques (see Table V.) Again, the compressive stress induced prevents fatigue cracks from propagating in the material surface. The increase in endurance limit, or fatigue strength, due to shot peening after metal removal ranges from 10% to 200%. It should be noted that processes such as grinding, grit blasting, honing and roller burnishing also provide fatigue benefit when compared to control specimens. Each of these processes induce surface residual compressive stresses. However, shot peening is able to improve fatigue resistance beyond that obtained by these processes (grinding, grit blasting, honing and roller burnishing). Improvement in endurance limit or fatigue strength due to shot peening <u>after</u> a potentially beneficial process ranges from 10% to 96%.

It should be stressed that shot peening should normally be done <u>prior to</u> a coating operation but <u>after</u> a metal removal operation.

SHOT PEENING RECOMMENDATIONS

It is vital that the residual compressive stress from peening extend <u>below</u> any surface cracks, pits, defects or stress raisers (see Figure 2). It is also important that the offsetting tensile stress not be allowed to become large enough to create early internal failures. Dr. Henry Fuchs defines "Optimum Peening Intensity" as that intensity which is high enough to arrest cracks started at the surface but not so high that it would start cracks below the surface (11). A couple of rules of thumb could be considered when selecting the depth of the compressive layer induced by peening.

1) The depth of the compressive layer from shot peening should be such that the maximum value of the compressive stresses are at, or below, the depth of the largest defect or stress raiser.

2) The area under compressive stress shall be less than 5% of the total cross section of that area of the part.

TABLE IV

EFFECT OF SHOT PEENING

Prior To Coating

Process	Base Material	Endurance Limit at 10^7 Cycles Control	As Coated	Shot Peened
Hard Anodize(1)	7075T6	24.6	14.6	29.0
Chrome Plate (3)	4340 steel 270 KSI	93.0	74.0	113.0
Nickel Electro-plate(5)	4333 steel 160KSI	13.5*	12.3*	27.5*
Plasma Spray Metro 450(6)	Titanium 6AL-4V	87.0	27.0	86.0

*Fatigue Strength at 3×10^5 Cycles

TABLE V

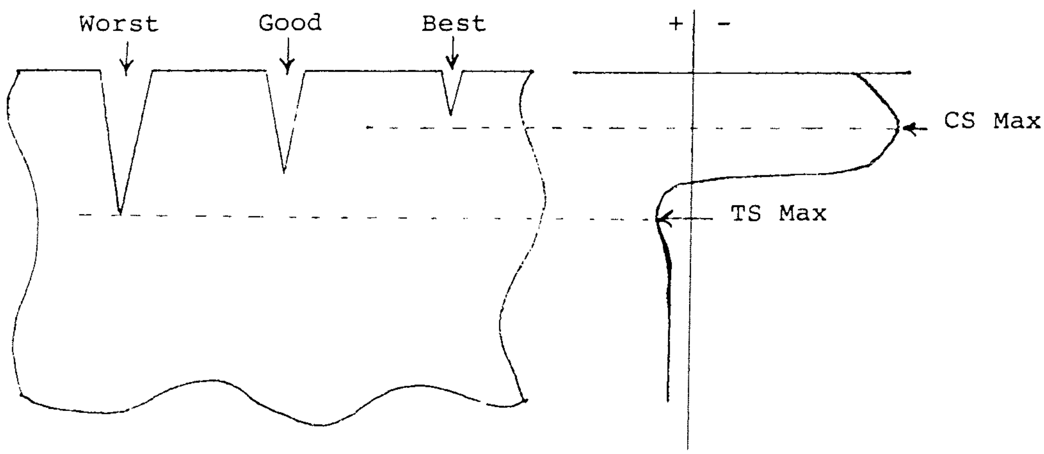
Effect of Shot Peening
After Metal Removal

Process	Base Material	Endurance Limit at 10^7 Cycles KSI		
		Control	As Processed	Shot Peened
ECM (8)	IN718	60.0	39.0	78.0
EDM (8)	IN718	60.0	22.0	66.0
Grinding (8) (Longitud.)	4340 steel (HRC50)	90.0	102.0	112.0
Grit Blast(6) (Al_2O_3)	Titanium 6Al4V	87.0	96.0	108.0
Honing (5)	4333 steel 160 KSI	13.5*	14.0*	27.5*
Pickling(9)	Magnesium AZ 91	12.0	9.5	15.0
Roller Burnish(5)	4333 steel 160 KSI	13.5*	17.1*	27.5*

*Fatigue Strength at 3 x 10^5 Cycles

Figure 2

Depth of Compressive Stress vs Defect Depth



CONCLUSION:

Controlled shot peening is effective in restoring fatigue strength debits due to finishing operations. In most cases, the shot peened material is improved even over the fatigue properties of the material prior to finishing. Finishing processes which are beneficial to fatigue resistance can also be enhanced by shot peening.

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