ACADEMIC STUDY

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Back to Basics: The "Magic Skin"

INTRODUCTION

The whole point of shot peening is to improve the service life of industrial components. Peening achieves this aim by inducing a "magic skin" into the components. This skin is a thin surface layer that has two defining characteristics—work-hardening and compressive residual stress. For too long it was assumed that compressive surface residual stress was the only significant factor. Nowadays it is recognized that work-hardening is an equally important factor. As a simple equation we have that:

WORK-HARDENING + COMPRESSIVE SURFACE RESIDUAL STRESS = INCREASED SERVICE PERFORMANCE

The term "magic skin" was coined to express the unique features of shot-peened surface layers. The word "Magic" is employed because protection is afforded without any visible indication of its presence. "Skin" is synonymous with the surface layer of all flora and fauna. Banana skin, orange peel and elephant hide exemplify the protection that they afford.

It is important to remember that shot peening cannot always improve the service performance of every component. By way of illustration, consider the term "Victorian Engineering". This was coined in the 19th Century during the reign of Britain's Queen Victoria and coincided with their Industrial Revolution. Many machines were constructed using iron or steel components that were so thick that maximum applied stresses were reduced below their fatigue limit. Fig. 1 illustrates this principle. Ferritic materials normally exhibit a linear shape of applied stress versus cycles to failure when plotted on a logarithmic scale. An applied stress level greater than the fatigue strength is required in order to cause failure. With "Victorian Engineering" the applied stress level never came near to the fatigue strength so that fatigue failure never occurs. Indeed, some mighty machines are still operating two centuries later. The drawback is that excessive amounts of material and energy are required for such machines. Shot peening comes into its own (thanks to the "Magic Skin") when the maximum applied stress levels would otherwise exceed the fatigue strength.

Fatigue is a massive subject in its own right so that only a very brief consideration is possible. To better understand the Magic Skin we should consider the separate effects of work-hardening and surface compressive residual stress.

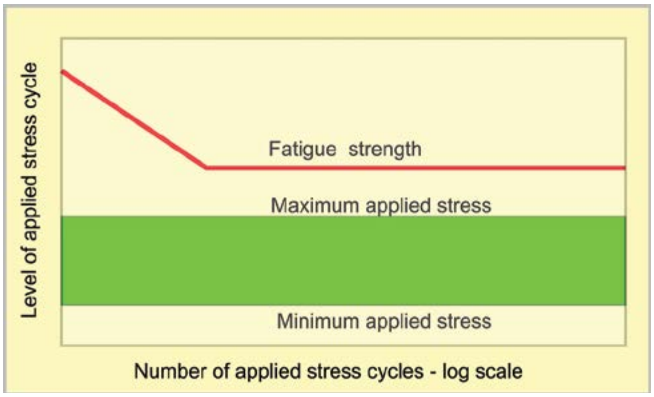


Fig. 1. Fatigue stressing below a component's fatigue strength.

WORK-HARDENING

Work-hardening involves two distinct factors: work and hardening.

Work

A flying shot particle has a kinetic energy, ½Mv^2, where M is its mass and v is its velocity. This kinetic energy allows the particle to produce a dent when it strikes a component's surface. The amount of kinetic energy is equal to the work that had to be done on the particle to accelerate it.

Example: A steel shot particle having a mass of 2 milligrams (roughly S330) and a velocity of 100 ms^{-1} will have a kinetic energy, k.e. given by:

$$\text{k.e.} = \tfrac{1}{2}.2.10^{-3}\text{kg}.10{,}000\text{m}^2\text{s}^{-2} = 10\text{kgm}^2\text{s}^{-2}$$

1N = 1$kgms^{-2}$ where 1N is 1Newton. Hence k.e. can be represented as $10kgm^2s^{-2}N/1kgms^{-2}$ or

$$\text{k.e.} = 10\text{Nm}.$$

By way of comparison, consider lifting up a 1 kg peening hammer, see fig. 2 on page 28, by a distance of 1 m. 1 kg exerts a force of 10N due to gravity. The work done in lifting the hammer is therefore 10Nm which is exactly the same as that

Fig. 2. Typical peening hammer.

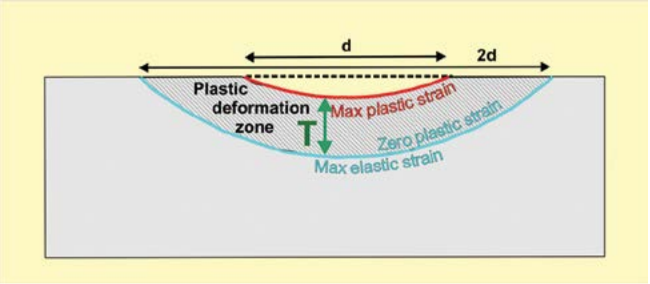


Fig. 4. Thickness, T, of work-hardened surface layer induced by shot peening.

which had to be done on the shot particle to accelerate it to 100ms^{-1}.

Hardening

Shot peening is a cold-working process. As such, the more work is done on a component the harder it becomes to do more work hence the term "hardening". Hardening is caused by the vast multiplication of lattice defects called "dislocations". As an analogy, think of traffic carrying passengers in a city. If the streets were almost empty traffic could flow freely. With more traffic, however, the more flow rates decrease. Eventually, traffic will stop.

The greater the amount of cold-work, the higher will be the applied stress required to induce further cold-work. This is illustrated for peening by fig. 3.

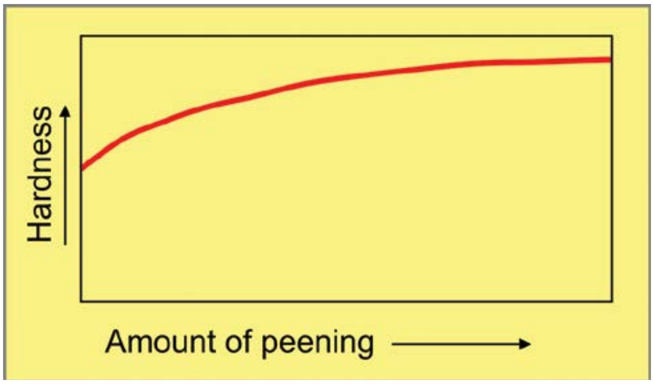


Fig. 3. Hardening depends on amount of peening.

Thickness of Work-Hardened Surface Layer

The thickness, **T**, of the work-hardened surface layer is proportional to the size of the indentations. This principle is illustrated by fig. 4. The amount of work-hardening increases with increase of amount of plastic strain.

COMPRESSIVE SURFACE RESIDUAL STRESS

Residual compressive stress occurs at the extreme surface of shot-peened components. The compressive stress level then increases to a maximum just below the surface. Thereafter the compressive stress level falls to zero and then becomes a balancing tensile stress. A model residual stress profile is shown in fig. 5. Stress levels depend upon the yield strength of the peened material. At the extreme surface, the compressive stress level is always about 50% of the yield strength. This compares with about 67% being reached below the surface. It is worth noting that the maximum compressive residual stress is often greater than the yield strength of the unpeened component material. This is because of the large rise in yield strength that occurs in the magic skin.

Depth of compressive stress below the surface depends mainly on the peening intensity.

The shape of the residual stress profile approximates to that of a cubic equation. For fig. 5 the equation used was:

$$\mathbf{S = -3335E4x^3 + 1.444669E^2 - 3000.5x - 500}$$

where **S**= stress and **x** = depth below the surface.

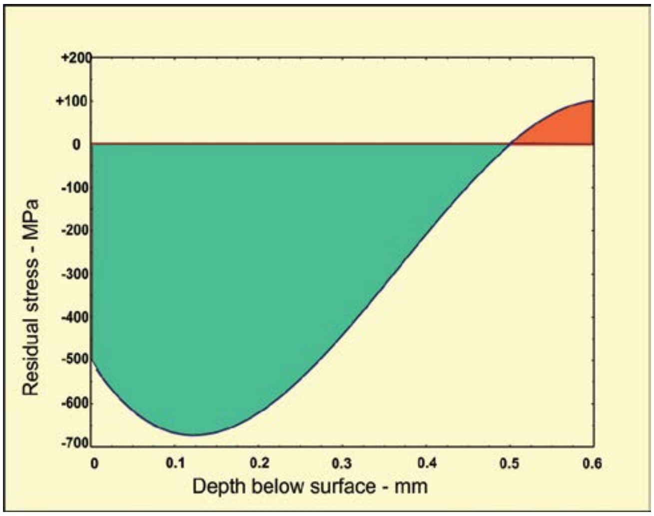


Fig. 5. Model of typical residual stress profile on peening.

Perhaps the most important question in the English language is "Why?" For a residual stress profile, a significant question is "Why is the compressive stress lower at the extreme surface than it is beneath the surface?" The author is not aware of any published explanation. Hence an attempt is made in the following section. This takes the form of a fictional tutorial given to a group of mechanical engineering students. It strays from being "Basic" so can be skimmed through. A simple equation is, however, presented:

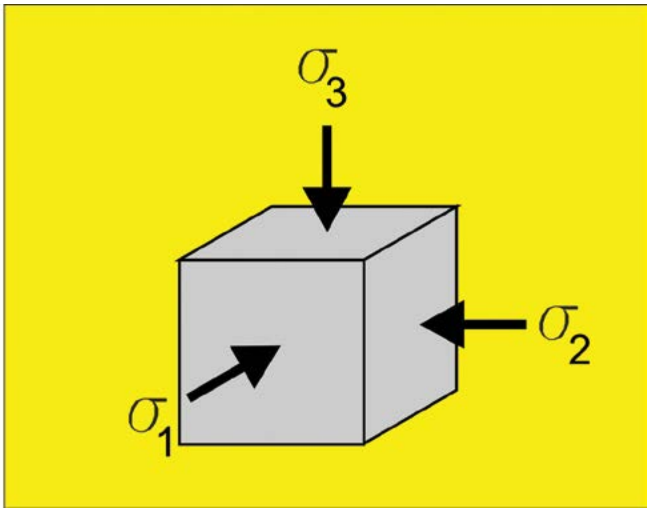
$$q_x = \Delta p_x - Y/2 \qquad (1)$$

where q_x is the residual stress just below the extreme surface and Δp_x is the change in the residual stress perpendicular to the surface.

Why is the compressive stress lower at the extreme surface than it is beneath the surface?

"By way of revision you all know what principal stresses are as displayed in Slide 1. They are three stresses applied perpendicular to the faces of a unit cube of material. Together they represent the "State of Stress" (**σ_1, σ_2, σ_3**). With only one stress being applied, the State of Stress is (**σ_1**, 0, 0). With two stresses being applied we have (**σ_1, σ_2**, 0).

With just one stress being applied, plastic yielding will occur if s_1 reaches the yield strength of the material, **Y.** For two or three stresses being applied simultaneously the situation is not so simple. We have to invoke what is known as a "Yield Criterion". The Tresca Yield Criterion is the simplest to employ for our purposes. Stated verbally, Tresca said that yield will occur if the difference between the largest and smallest principal stress reaches the yield strength of the material. As an equation, we have yielding when **$Y = (\sigma_1 - \sigma_3)$** where **$\sigma_1$** and **$\sigma_3$** are the largest and smallest principal stresses. Which is the largest principal stress for a state of stress (0, 0, q) where q corresponds to a compressive stress? The answer is 0. A bank overdraft corresponds to a minus quantity so you would be much happier to have a zero amount than a negative amount. Applying the Tresca yield criterion we now have yielding when $(0 - q) = Y$ or $q = Y$ with Y being the compressive yield strength.



Slide 1. Principal Stresses.

Remember that stresses are additive. For example, stresses of +200MPa and -100MPa acting in the same direction add up to +100MPa.

Revision over, we can now go on to tackle our problem.

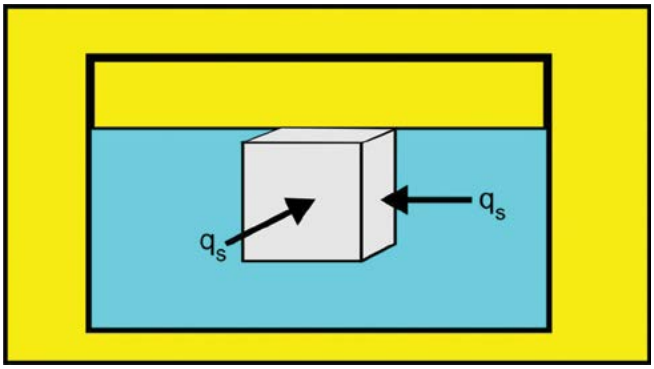
The state of stress at the extreme surface of a shot-peened component is (0, q_s, q_s) with q_s being compressive. The stress perpendicular to the extreme surface is always zero and the two compressive residual stresses act parallel to the component's surface. An important property of residual stresses is that their maximum value is always much less than the stress, Y, needed to cause plastic deformation. As a guide, the compressive residual stress at the extreme surface can only reach half of Y but reaches two-thirds of Y at some point below the extreme surface.

Below the extreme surface the state of stress starts to change. Δp is the change in the residual stress perpendicular to the surface and q_x is now the compressive residual stress acting parallel to the surface. Our key question is "What is the maximum level of compressive residual stress that can be tolerated below the extreme surface where the state of stress is now three-dimensional?" Before tackling that question consider the following analogy. A survey is to be carried out on student height variation for groups of three. Results have to be presented in the format of "State of Height" (h_1, h_2, h_3) where h represents height. For one trio their heights are 6 feet, 5 feet and 5 feet represented as (6, 5, 5). These values can also be presented as (5, 5, 5) + (1, 0, 0). For height variation, we can ignore the first term, (5, 5, 5). This leaves us with simply (1, 0. 0) as the only values representing height variation. The (5, 5, 5) has no effect. This is obviously trivial mathematically, but reveals a vital principle that we can now use to solve our peening problem. To answer our peening problem, we again manipulate the state of stress in order to find an <u>effective</u> state of stress. The state of stress at the extreme surface of a shot-peened surface is two-dimensional and can be expressed as (0, q_s, q_s) where q_s is the residual stress parallel to the extreme surface. Experimental evidence tells us that q_s is approximately equal to half of the yield strength, Y. Applying Tresca's yield criterion we therefore have that $(0 - q_s) = Y/2$ or $q_s = -Y/2$. The state of stress below the extreme surface becomes three-dimensional and can be expressed as (Δp_x, q_x, q_x) where Δp_x is an increment of residual stress perpendicular to the surface and q_x is the maximum residual stress parallel to the surface that can be sustained. Now $(\Delta p_x, q_x, q_x) = [0, (q_x - \Delta p_x), (q_x - \Delta p_x)] + (\Delta p_x, \Delta p_x, \Delta p_x)$ and, ignoring the second term as not contributing to stress limitation, we have: $[0, (q_x - \Delta p_x), (q_x - \Delta p_x)]$. Applying Tresca's yield criterion gives us: $q_x - \Delta p_x = -Y/2$ or $q_x = \Delta p_x - Y/2$.

$$q_x = \Delta p_x - Y/2 \qquad (1)$$

Let us now assume that Δp_x corresponds to a compressive residual stress. Using imagined quantities of -10MPa for Δp_x and 500MPa for Y, equation (1) tells us that q_x = -10MPa – 250MPa or q_x = -260 MPa. That compares with -250MPa (Y/2) at the extreme surface indicating an increase in compressive stress level below the surface. This does, however, rely on the assumption that Δp_x is a <u>compressive</u> residual stress. A basic rule in both science and engineering is that we should be able to validate any assumptions made.

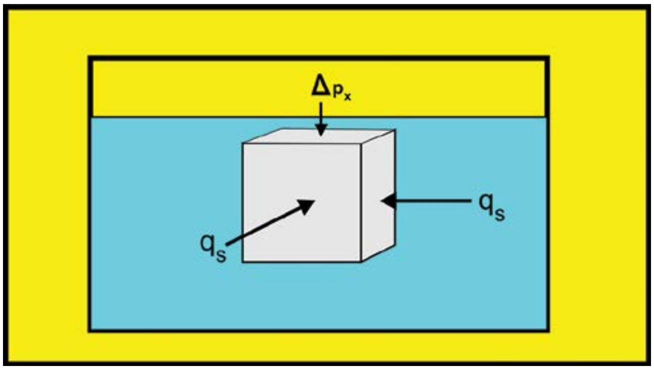
Consider the analogous situation illustrated in slide 2. A cube of material having exactly the same density as water (1g/cc) is placed carefully into a tank of water. The cube just stays at the water's surface. There it is subjected to a two-dimensional state of stress (0, q_s, q_s) with the pressure of water corresponding to the compressive stress, q_s.



Slide 2. Two-dimensional cube stressing at surface of fluid.

Now imagine the cube has been pushed down to just below the water's surface. Pushing the cube down requires a compressive stress, Δp_x. We now have the situation illustrated in slide 3.

If it helps to get the idea, think of an aquarium with a cube of fish food either floating at the surface or being pushed below the surface of the water.



Slide 3. Three-dimensional stressing below surface of fluid.

Assumption justified, albeit analogously!

End of tutorial – let's go for a beer.

FATIGUE OF COMPONENTS

Fatigue of metallic components has a parallel with that of humans in these pandemic times. We get fatigued by the cycles of stress associated with lockdown. The higher the levels of stress the lower are the number of cycles needed to cause fatigue. If the combination of stress level and number of cycles is severe enough, we can exceed our endurance limit and simply crack up. Similarly, for metallic components when the combination of stress level and number of cycles exceed their endurance limit they also crack up.

The fatigue behaviour of metallic components is commonly represented in the form of S-N curves where S is the level of stress and N is the number of stress cycles. A simple version is shown as fig. 6. Note that both x and y coordinates use a logarithmic scale.

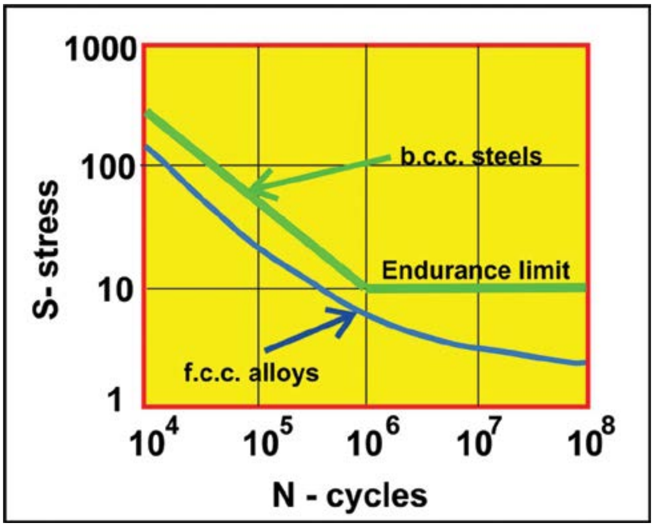


Fig. 6. S-N fatigue curves.

Different types of material have different shapes of S-N curve. Two characteristic shapes are shown in fig. 6. A range of from 10^4 to 10^8 cycles is commonly employed. At 50 cycles per second it takes about 3 minutes to apply 10^4 cycles, 5 hours to apply 10^6 and about 23 days to apply 10^8 cycles.

The significance of the number of cycles involved depends upon the use to which the component is being employed. Blades of an aero engine, for example, typically rotate at about 104 r.p.m. Knowing the cyclic stress required to induce failure in one minute is of little practical use! Running times between overhauls are about 4,000 hours or 240,000 minutes. At 10^4 r.p.m. this corresponds to stress cycles of about 2,400,000,000 or 2.4 x 10^9. Testing at 50 cycles per second would take over a year. By way of contrast, aircraft landing gear is subjected o far fewer stress cycles so that stress to induce failure after 10^4 cycles is now relevant.

Fatigue testing to high numbers of cycles does not rely on mains frequency. Two main approaches are to use either high-speed rotation under load or resonant frequency push-pull. The rate of loading does, however, affect the cycles to failure. Work is being done on the test sample during every stress cycle. Some of this work generates heat in the sample, raising its temperature.

A notable feature of fatigue tests is the amount of variation in cycles to failure that occurs when repeat tests are carried out at the same stress level. A variation of a thousand to one is not uncommon but is less obvious on S-N curves because of the logarithmic scale being employed. Surface condition of test specimens is a critical factor so that electropolishing is often employed. The surface condition of peened test specimens is then quite different from that of polished specimens.

Shot peening generally increases the stress required to induce failure at a given number of cycles as illustrated schematically in fig. 7.

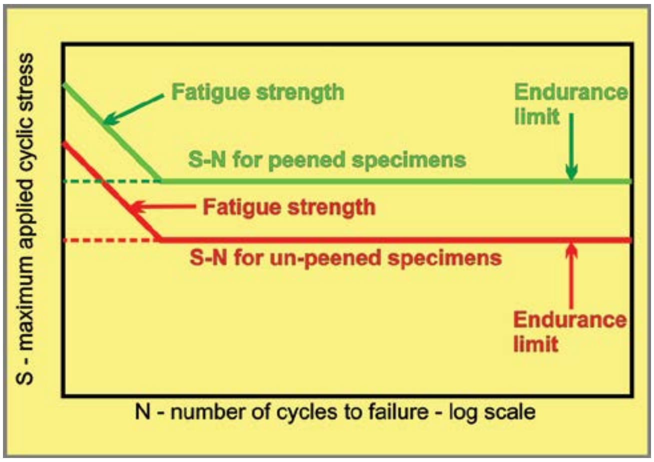


Fig. 7. Schematic of effect of shot peening on S-N curves.

A basic feature of fatigue tests is the large scatter of results. This is evidenced by the actual data presented in fig. 8. Consider the three data points for unpeened specimens tested at 200MPa. Failure occurred at 110,000, 2,000,000 and 2,100,000 cycles. Translating these figures to Almen arc height scatter would give 0.11 mm, 2 mm and 2.1 mm!

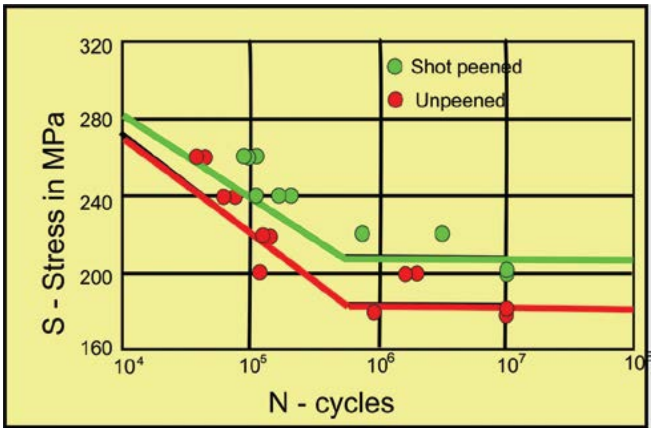


Fig. 8. Test data for effect of shot peening on S-N curves.

COMBINED EFFECT OF WORK-HARDENING AND COMPRESSIVE SURFACE RESIDUAL STRESS

Shot peening produces the double-headed benefits to fatigue life of both work-hardening and compressive surface residual stress. In service, components are normally subjected to both alternating stress and a fixed loading stress. This is illustrated by fig. 9. Imagine a railway wagon being pulled along a track using a force P. This will impose cyclic stressing—shown as S—with stress level increasing with increased track roughness. The weight of the wagon will impose a force, F, on the wagon's springs which translates to a constant applied stress. Goodman diagrams give us a neat way of combining these two effects of cycling and constant applied stress.

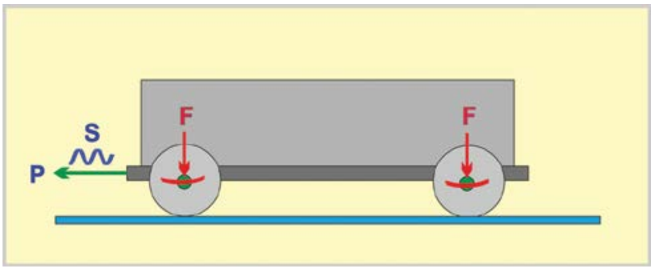


Fig. 9. Schematic of wagon spring fatigue cycling.

A basic Goodman diagram is shown as fig. 10. An area, such as the red one, indicates that the material should not fail given the combination of applied stresses. The area above the area represents likely failure.

Imagine a wagon, having unpeened springs, being progressively loaded. Eventually the springs would collapse, as their yield strength was reached at point A. No cyclic stress could then be applied before the train even started. Now consider what happens if the springs had been shot peened. The "magic skin" raises the stress at which the springs would collapse by AB and BC. More realistic wagon loading is indicated by E, M and H corresponding to Empty, Medium, and Heavy loading respectively. The fatigue strength, F.S., of the springs is correspondingly raised, from A to B and C. For wagons in motion the applied cyclic stress will increase as track roughness increases.

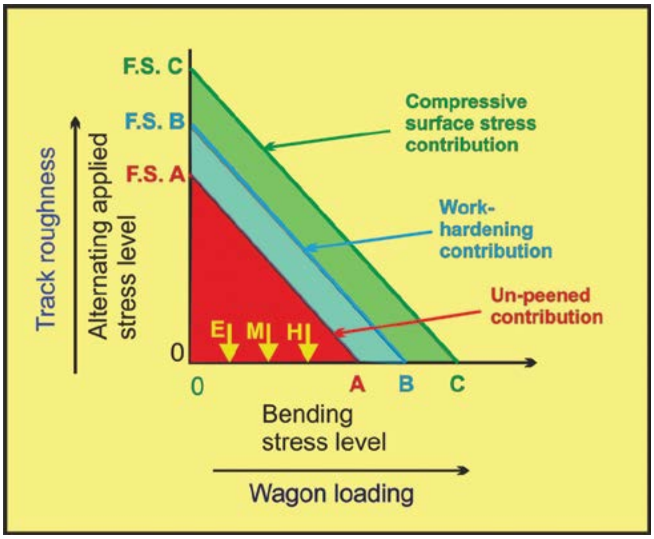


Fig. 10. Goodman diagram modified to show separate contributions.

DISCUSSION

This article has attempted to explain how the magic skin produced by shot peening increases the service performance of components. Of necessity, the treatment is relatively superficial. It tries, however, to stay within the framework of "Back to Basics." It cannot be stressed too highly that the "magic skin" works because of equally-important contributions from work-hardening and compressive residual stress.