90106

An Explanation of the Mechanism and Benefits of Shot Peening

It is possible to enhance certain properties of some materials to enable them to better meet the needs of critical designs. Most of us are familiar with the use of heat treatments to improve the properties of metal alloys. Such treatments can be used to increase the hardness of a knife blade so that it will remain sharp for a longer period of time than will an untreated blade. Similarly, the strength of a bolt can be increased through heat treatment so that a smaller bolt can be used in an application that would otherwise require a much larger bolt.

Another process that is used to improve material properties is "shot peening" which is the process in which hard shot is hurled against a work surface. In this case the properties that are enhanced are resistance to fatigue fracture and resistance to stress corrosion rather than strength or hardness.

Traditionally, shot peening is done by spraying hard shot against a work surface in a fashion similar to sand blasting. Shot peening can also be done with "captive shot" where the shot is integrated into a rotating brush or flap. In this case the spinning brush or flap is placed in close proximity to the work surface so that the captive shot strikes the work surface with each revolution.

In order to understand the beneficial effects of shot peening one must first understand the mechanics of surface stresses, and the effect that peening has on these stresses. To this end, the following discussion of these concepts is presented. The details of both fatigue failure, and stress corrosion will also be reviewed but not until after a preliminary discussion on surface stresses.

Surface Stresses and Peening

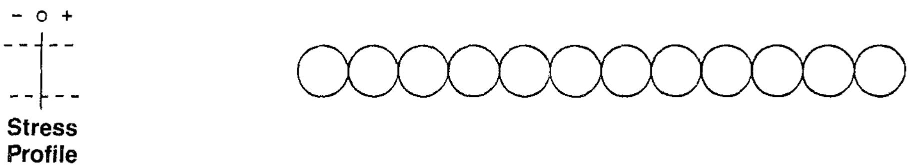
As a means of understanding the concept of surface stress, and the beneficial effects of peening, one can begin by individually taking a close look at the concepts of "peening", "compressive stresses", and "tensile stresses".

Peening: "Peening" means nothing more than to hammer. Shot blasting or rotopeening effectively hammers a surface, although with very small hammers, and with a large number of strokes.

Compressive Stresses: Most people are probably familiar with the concept of compression but probably with different considerations. Compression means nothing more than to squeeze together. If a part is squeezed in a vice, it is subjected to compressive stresses.

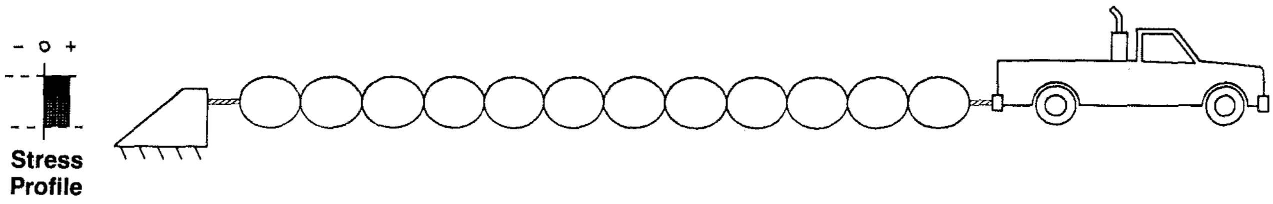
Tensile Stresses: Most people are probably also familiar with the concept of tension, which results from pulling forces. A tightly-stretched wire is subjected to tensile stresses.

As an aid to better understanding the concepts of compression and tension, consider a very fine bar of metal. A bar so fine, in fact, that it is composed of a single string of atoms. To understand how such a bar will function, consider that the atoms behave like very-small, sticky, and flexible spheres, much like small rubber balls coated with adhesive.



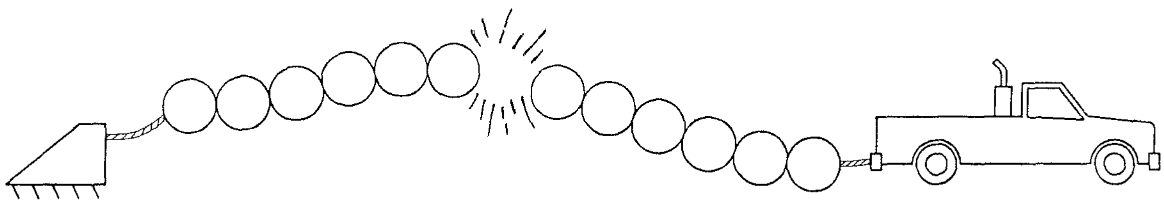
Stress-Free Bar, one atom thick

Here is such a bar in a stress-free condition. It is stress-free because there are no compressive or tensile forces acting on it. A "stress profile" is used to indicate the level of stress over the entire cross-section of the bar. In this case, the small graph to the left of the bar is the corresponding stress profile. Convention calls for compressive stresses to be given negative values, and for tensile stresses to be given positive values. In this first example, there are no stresses as is indicated by the neutral stress profile. It will be found that the stress profile will change as some work is done on the bar, and the stress profile will be the source of some very valuable information. Begin by considering what will happen if the bar is placed in tension, as it would be if one end were secured and the other end were pulled on by a rope.



Bar Under Tensile Load

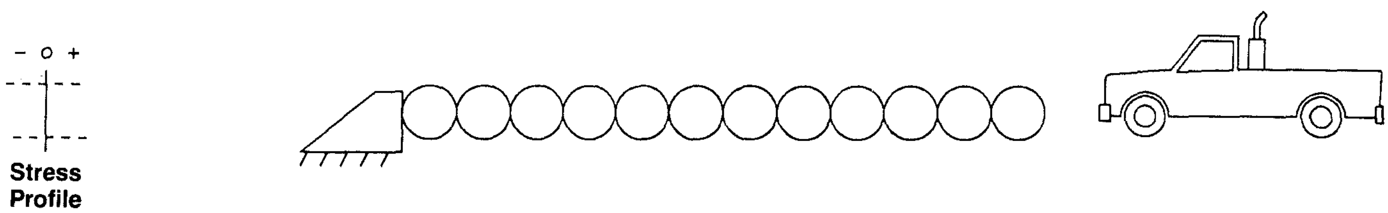
The bar was pulled on. The individual atoms elongated, and the whole bar got longer. The atoms are under tensile stress. This is shown by the stress profile diagram. Notice that the stress profile diagram indicates that the entire cross-section is under tensile stress. Continue by further stretching the bar.



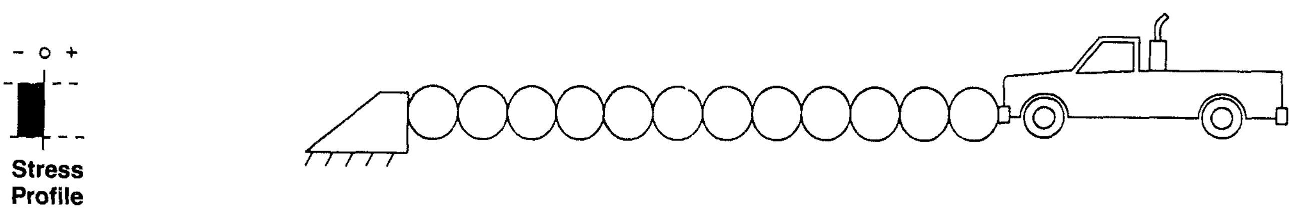
Bar Breaking Under Excessive Tensile Load

Here the applied tensile forces exceeded the forces that bound the atoms together and the bar broke. This is how fracture occurs. When tensile forces between atoms, are greater than the forces that bind them together the atoms separate and the piece breaks.

Now, let us examine compressive forces. Begin by considering what will happen if one end of the bar is secured against a block, and the other end is pushed on until the bar has been shortened by one atom diameter.

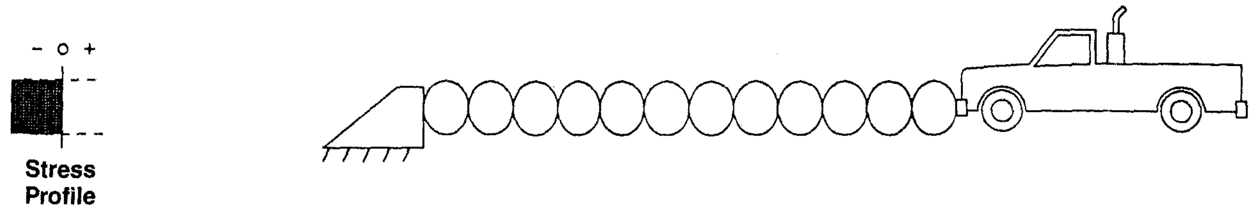


Stress-Free Bar Before Compression



Bar Under Compressive Load

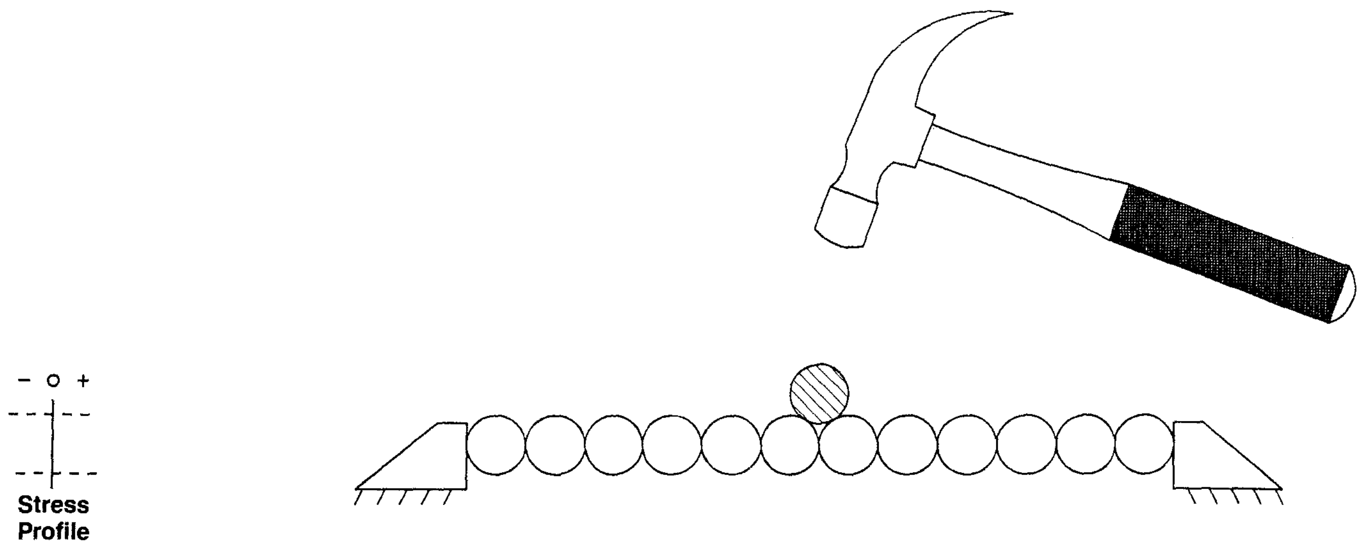
Notice what happened. The bar was pushed on and as a result the atoms got a little narrower and a little taller as the bar got shorter. These atoms are now under compressive stress. But remember that atoms are springy, and that they would rather be round. They are pushing against the blocks and if the blocks were removed the bar would return to its original length. What if the experiment is continued and the bar is compressed an additional distance?



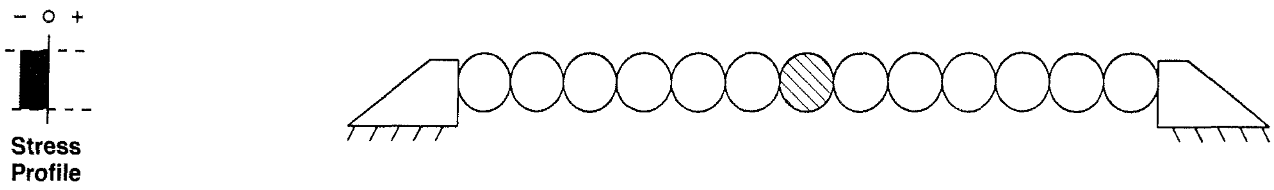
Bar Under High Compressive Load

Notice that again the atoms got narrower and taller as the bar got still shorter. Notice also how the compressive stress also increased (as is indicated by the stress profile diagram), but the bar did not break, as it did when excessive tensile forces were applied! A crack can never form in a bar where there are only compressive forces. The bar may eventually "buckle", but failure by crack propagation will not occur.

Is there another way in which a compressive stress can be created in the bar? What if each end of the bar were restrained and another atom placed on top. If this extra atom is then knocked into place, the new atom and all the original atoms will be compressed.



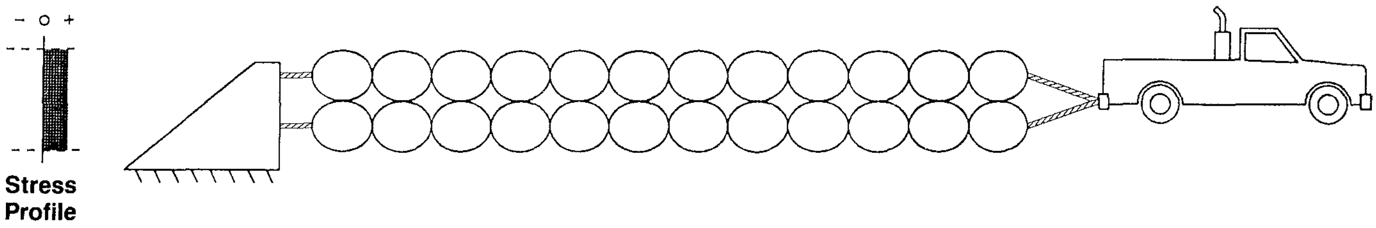
Stress-Free Bar, Restrained At Each End



Restrained Bar After Insertion Of One Atom

Sure enough, the bar is now in compression. In fact, it looks just like it did after it was compressed by the movable block in the previous example. Also, since it is in compression, the atoms want to return to their unstressed state and try to do this by pushing on the fixed blocks. This is essentially what happens when a part is peened. Surface atoms are driven into the part, and the surface is put in compression.

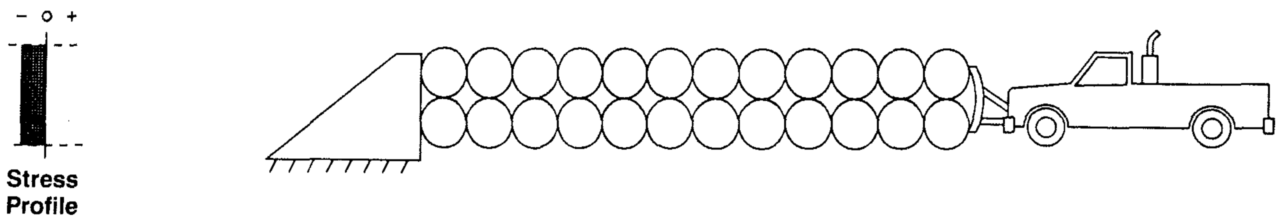
So much for tensile and compressive stresses on a small bar. Now consider a bigger bar, one that is two atoms thick, and see what happens when it is put in tension.



Bar, Two Atoms Thick, Under Tensile Load

When a tensile force is applied to the bar it elongates, just as it did before. Notice that the tensile stresses are distributed uniformly across the cross section of the bar. This is shown in the stress profile.

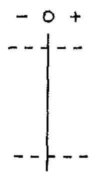
What about placing the bar in compression? This can be done just as before by blocking one end , and then pushing the other end in the distance of one atom diameter.



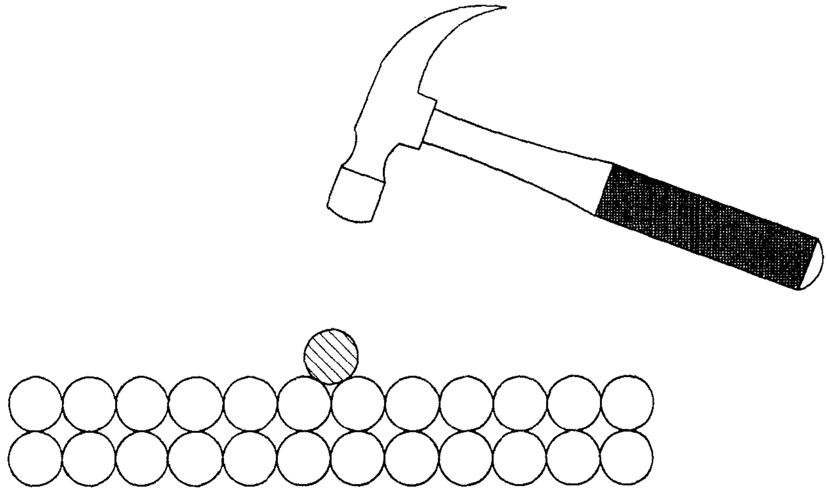
Bar, Two Atoms Thick, Under Compressive Load

As in the previous case involving compression, the individual atoms got narrower and taller. Notice that the compressive stresses are distributed uniformly across the bar's cross section, as is shown in the stress profile.

What would happen if an additional atom were squeezed into the top layer? This could be done without securing the bar between blocks, or pulling on it with a rope. In other words, no external forces (and therefore no external stresses) need be applied to the bar.

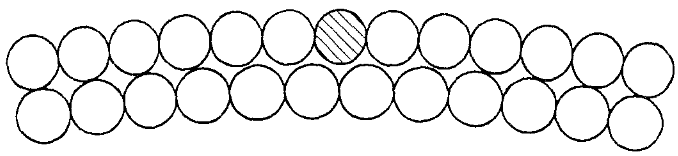


Stress
Profile



Unrestrained Bar Of Two-Atom Layer Thickness

Stress
Profile

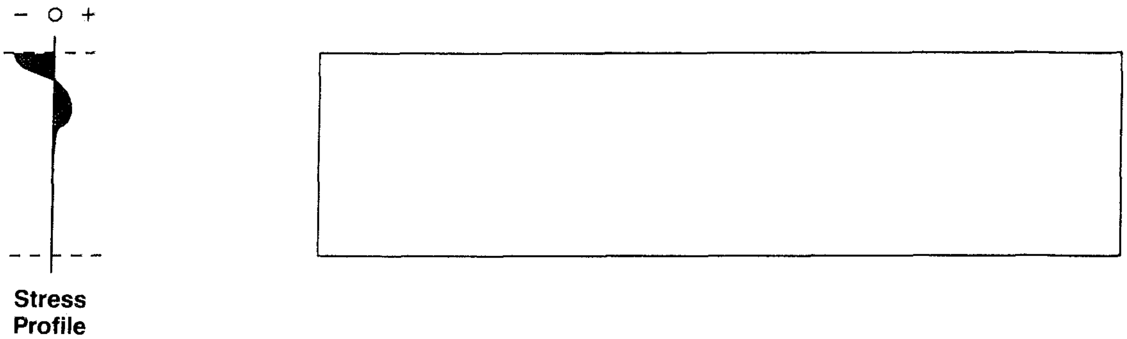


Unrestrained Bar Of Two-Atom Layer Thickness After Insertion Of One Atom Into Top Layer

This is very interesting. The top layer is in compression, just as when the bar was a single layer between blocks. Apparently, the bottom layer is able to restrain the top layer as had the blocks in the earlier example. But look at the bottom layer! In restraining the top layer, the bottom layer gets stretched. Look at the stress profile diagram. It verifies our suspicions, showing that the top layer is in compression, and that the bottom layer is in tension.

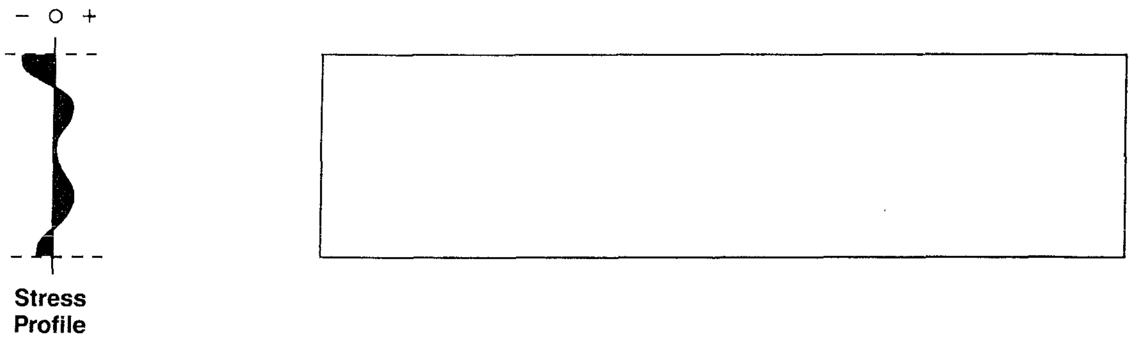
Notice something else. The top layer elongated because of the additional atom. The bottom layer also elongated, but not quite as much as did the top layer. Since both layers are tightly bound together, this difference in elongations caused the bar to bend.

Consider what would happen if the bar were too thick to bend. The top layer would still be in compression, and the layer immediately below would still be in tension. The core would be unaffected, and without external forces, would be under no stress.



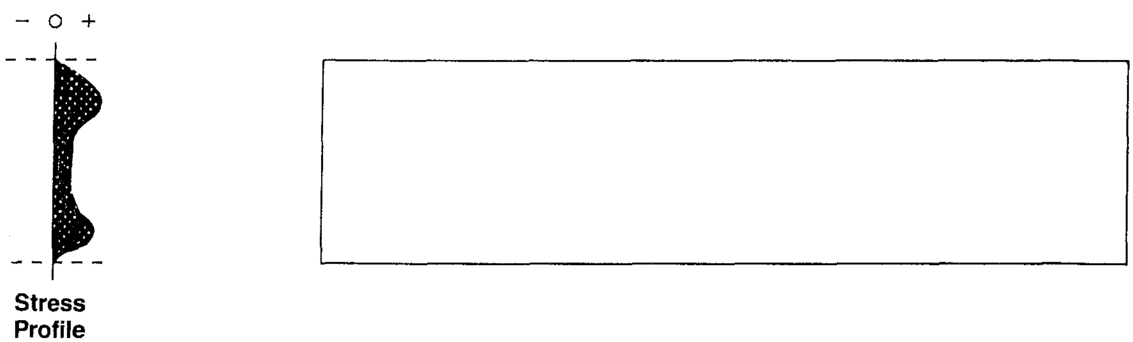
Large Bar Peened On Top Surface
(atoms are now too small to be individually seen)

To further extend this experiment, consider a very large bar that has been peened over its entire surface. Such a bar is shown below, along with its stress profile diagram. Notice that the outer layer is in compression, the layer just beneath the surface is in tension, and the core is under no stress.



Large Bar Peened On All Surfaces

Now, consider what will happen to such a bar if it is put in tension. This would happen if something useful were done with the bar like using it to suspend a bridge deck from a truss.



Large Bar Peened On All Surfaces
Subjected To A Tensile Load

By putting the bar in tension, tensile forces were added to the entire cross section. The core, formerly unstressed, now sees a uniform tensile stress. The layer just below the surface, formerly in tension, now sees even greater tensile forces. The outer layer, formerly in compression, is now neutral - that is under no stress at all!

That is remarkable! By peening the surface of a bar, it is possible to create conditions that result in zero surface stresses, even when the bar is under a total tensile load. More than remarkable, this is highly practical. Remember that cracks form, and structures fail only where tensile stresses exist. Tensile stresses are especially detrimental if they occur where small cracks (or even scratches) already exist. These cracks elongate when they are exposed to tensile forces, especially if the tensile forces are cyclical in nature. There will always be scratches on the surface of a bar. There should, however, be no scratches inside of a bar. If conditions exist such that tensile forces are not on the bar surface, then any pre-existing surface imperfections will not be caused to grow. By keeping the outer layer in compression, it is possible to greatly increase the performance characteristics of a given structure.

It should be pointed out that if the surface crack goes through the compressive layer, that it will enter the area of high tensile stress, and catastrophic failure will likely occur. It is for this reason that defects must be removed if peening is to have desirable effects.

Metal Fatigue and Stress Corrosion

Metal fatigue was alluded to in the previous discussion when crack propagation, as a result of cyclical tensile stresses, was mentioned. It is actually the growth of small cracks that causes a structure to fail in a fatigue mode. Since such a structure would have been able to previously withstand much greater loads, this mode of failure was originally interpreted as a tiring or weakening of the metal. In actual fact, the metal is just as strong as it ever was. Failure occurred because unobserved and growing cracks effectively reduced the cross section of the member until it no longer was able to support the previously acceptable load.

If you watched ten-thousand logging trucks cross a highway bridge, and then the same bridge failed with just you and your Volkswagen on it, you could reasonably assume that you were the victim of a fatigue failure. What probably happened was that some initial flaw in a critical member was caused to grow each time a truck passed and put the part in tension. The crack increased in size with each additional truck until the truck just before you caused the crack to grow to such an extent that the critical member was not able even to support the load of you and your ill-fated vehicle. If the part had been treated so that its surface never saw tensile stresses great enough to cause crack propagation, then fatigue failure would not have occurred.

Stress corrosion is a higher class of corrosion than the type that most people are familiar with. We know that iron will corrode if it is exposed to salt water. In this situation only two things are required - a substrate (in this case iron), and a corrosive agent (in this case salt water). For stress corrosion to occur, three things are necessary. As before, both a substrate and a corrosive agent are required, but there is the additional requirement that the substrate be under a tensile stress. If only the corrosive agent, or only the tensile load is present, stress corrosion will not occur. In other words, if either the tensile stress or corrosive agent is prevented, then stress corrosion also will be prevented.

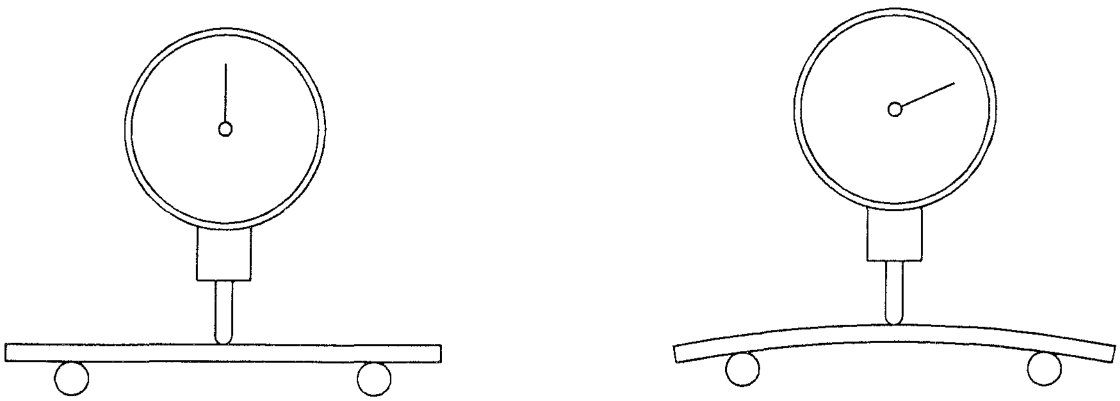
Some stainless-steel alloys are subject to stress corrosion where the corrosive agent can be what would otherwise be harmless environmental salts. Corrosion is prevented by assuring that parts that are exposed to the environment never experience tensile stresses. In the case of aircraft landing gear, this is done by shot peening the exposed surfaces. This is why it is vitally important to repeen any areas in which corrosion or other defects were ground out. Not only did the grinding operation remove the surface defect, but it likely removed the compressive stresses that had been imparted with the original peening. If the area is not properly repeened, then corrosion can be expected to reoccur, and will probably occur much more rapidly the second time around.

Since both metal fatigue and stress corrosion require surface tensile stresses, shot peening of susceptible surfaces is recognized as a viable method of preventing this type of damage. Shot peening works because the surface compressive stresses it produces counteract any tensile stresses that the part might normally experience.

Peening Intensity Measurement

As with most treatments (tempering, coating and even suntans) it is necessary to have some means to quantify the intensity of the operation. Unlike a small bar, structures normally peened are large enough that they will not deform as a result of the peening process. There is no test that can easily be done to a peened structure that will give an indication of the degree to which it has been peened. Compare this situation to a coating process (like applying paint) where it would be possible to measure the thickness of the resulting layer in order to gain an understanding of the quality of the process.

As a possible means of measuring peening intensity, recall how a small bar will curve as it is peened. If it is peened a little it will curve a little. If it is peened a lot, it will curve a lot. This phenomena also occurs in bars that are much more than two atom layers thick. If a steel strip 1/16 inch thick is peened on one side, it will develop a curve proportional to the degree to which it has been peened. This observation provides a means by which peening intensity might be determined. It should be possible to take a small bar (call it a test strip) and measure its curvature, before and after peening. (Hopefully, it will be flat before peening.) The curvature could be measured by supporting it between two points about 1.5 inches apart, and then using a dial indicator to measure the deflection at the center. This is the theory behind "Almen" testing. In Almen testing, the curvature of a standard test strip is measured before and after peening. The curvature is measured in thousandths of an inch over a specified span, and the resulting number is used to specify the Almen intensity.



Measurement Of Curvature Of Peened Test Strip

In this case the test strip was peened and the center deflected .012 inches. By convention, this degree of curvature results from a peening intensity of Almen 12 (the deflection of the test strip in thousandths of an inch).

So how could a large structure be peened to Almen 12? This could be done by setting up conditions that would cause the Almen test strip to be peened to an intensity of Almen 12. These conditions will include the speed of the shot, the area of the Almen strip, and the duration of the process. These conditions will then be applied to the Almen strip to see if indeed it curves 0.012 inches over the test span. If it does, then these same conditions will be applied to the peening process of the large structure. The shot speed must be the same, but the duration may be different. This is because the large structure will likely be a different size than the Almen strip. If it has twice the surface area, it will be necessary to peen it for twice as long. If it has ten times the surface area, it will be necessary to peen it for ten times as long. At any rate, the time per area will be identical to that used to peen the Almen strip. By maintaining tight control of the processing conditions, we are then assured that the peening intensity achieved in peening the large structure will be the same as the measured intensity achieved in peening the Almen strip.

To go back to the the paint analogy, this would be like using a spray gun to paint a surface on which it would be difficult to measure the thickness of the resulting coating - a house, for example. We could get around this problem by first painting a test strip on which we could easily measure the paint thickness. When the conditions that result in the correct coating thickness are determined (in this case paint flow rate, and again time per area) then these same conditions will be applied in painting the house. It will be inferred that the paint thickness on the house is the same as the paint thickness on the test piece. This is precisely the logic behind Almen strip testing.

The purpose of this paper has been to give the reader a basic understanding of the theory behind shot peening. Additional information, and specific operating conditions, can be found in the 3M Surface Conditioning Notes - "3M Brand Roto Peen Flap Assemblies Type TC 330".

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