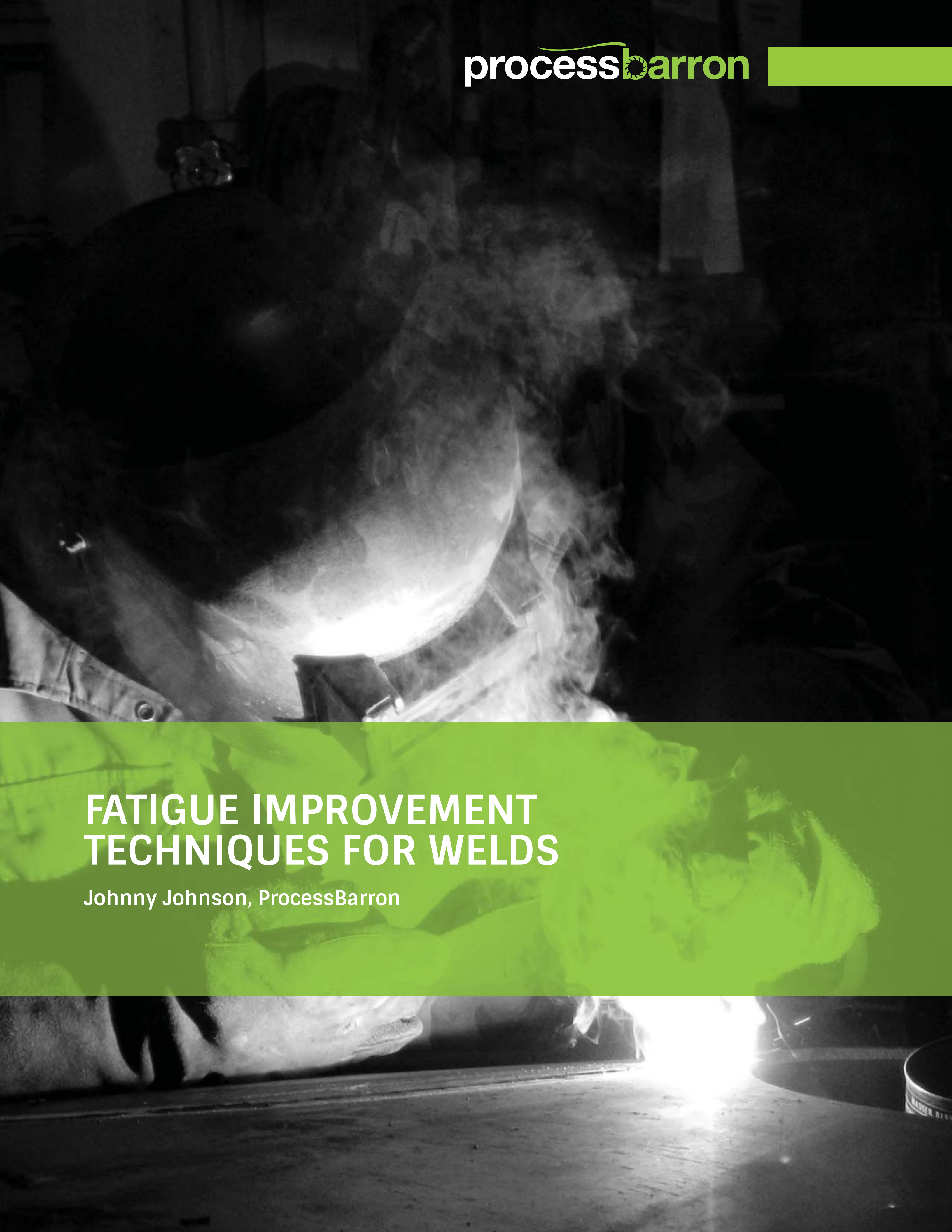

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FATIGUE IMPROVEMENT TECHNIQUES FOR WELDS

Johnny Johnson, ProcessBarron

SYNOPSIS

Most industrial machines and the structures that support them are subjected to fluctuating loads over their lifetimes. The vast majority of these machines are assembled, at least in part, by welding, which means that their welded joints must sustain changing loads over their lifetime. This represents one of the greatest challenges in designing for these conditions since welding inherently lowers the fatigue life of any structure.
This issue can be addressed with proper fatigue improvement techniques for welds, which this paper catalogs and assesses.

FATIGUE LIFE IMPROVEMENT TECHNIQUES FOR WELDS

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Introduction

Most industrial machines and the structures that support them are subjected to fluctuating loads over their lifetimes, even if nothing more than the cyclic loading associated with starting and stopping. The vast majority of these machines are assembled, at least in part, by welding, which means that their welded joints must sustain those changing loads over the life of the machine. Even if the machines are designed with appropriate safety factors against the static loads they must carry, they can fail prematurely due to fatigue cracking that results from fluctuating loading.

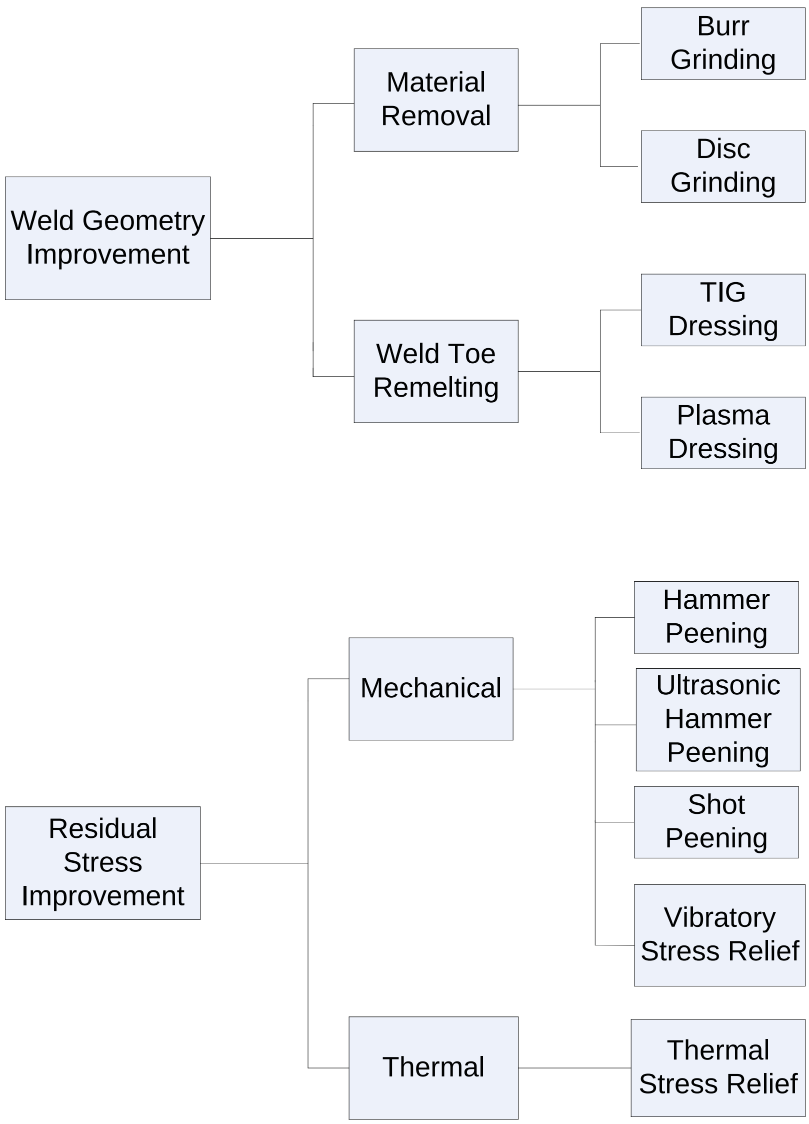
One of the greatest challenges in designing machinery or structures for these conditions is that welding inherently lowers the fatigue life of any structure. Statistically, a certain number of weld defects are expected in every weld; typically, weld defects introduce additional stress concentrations. Further, welding introduces residual stresses into the weld and surrounding structure; even mildly restrained welds develop peak residual stresses at or near the yield strength of the metals being welded. Research has clearly demonstrated that the fatigue life of metals is very sensitive to stress concentrations and residual stresses in the high cycle regime (above ~10^6 cycles) (1,2,3).

The trend in industrial machinery design over the past thirty years has been to increase process flows, pressures, temperatures, speeds, and intervals between maintenance, while demanding lighter, stronger, more wear resistant construction. The result is that machines are designed with much smaller safety factors and much greater attention to detail than ever before. When machines could be designed with extremely large safety factors, the need to consider fatigue life was minimal – the static and dynamic stresses were frequently so low that no combination of ordinary loads could produce a fatigue crack; today, the fatigue life of the machine is an important design consideration.

In most industrial designs, it is highly impractical to require that all welds be inspected at a level that will guarantee perfection; it is also impractical to require that all welds be ground smooth or polished to a mirror finish. This can leave the machine designer in a dilemma: how can the machine achieve its expected life and still be manufactured within reasonable time and financial constraints? One answer is that the welds in the machine can be minimally altered in ways that greatly enhance the fatigue life of the machine. This paper will catalog some of the more practical methods of weld improvement techniques and the benefits they promise.

One caveat that should be stated clearly from the beginning: many of the improvement techniques discussed in this paper are more beneficial in those cases where the desired fatigue life exceeds ~50,000 cycles. In the very low cycle fatigue regime, there is often yielding on every cycle, which may negate some or all of the benefit achieved by the methods discussed here.

These methods can be divided into two broad categories – those that address the geometric problems (i.e. the stress concentrations), and those that address the residual stress problems. The chart in Figure 1 presents these methods.



Weld Geometry Improvement

Typical, as-deposited welds do not create a smooth transition between the elements they join. Even the best welds with the smoothest surface conditions create a significant discontinuity between the parent materials they join together. Niu and Glinka (4) proposed the following relationship for the stress concentration factor at the toe of a weld: $K_t = 1.0 + 0.5121 \cdot (\theta^{0.572}) \cdot 0.217 \cdot (t / \rho)^{0.469}$
Where: K_t is the stress concentration factor

θ is the angle the toe of the weld makes with the adjacent member (radians)

t is the plate thickness

ρ is the weld toe radius

Other researchers (5,6,7) have reported typical values of these weld toe parameters for manual welds as being in the range of $\rho = 0.004$ to 0.008 inches and $\theta = \pi/4$ radians (45˚). Using these typical parameters and a range of plate thicknesses from $t = 0.1875$ to 1.5 inches, the stress concentration factor, $K_t = 1.4$ to 2.6. The effect of such stress concentrations on the fatigue life of welded specimens is illustrated in Figure 2. In this figure, the comparison is made between the fatigue strength of as-rolled plate material and as-welded specimens for a typical ASTM A-514 alloy. The permissible level of dynamic stress for the as-welded condition is a small fraction of the yield strength of the parent material.

Fatigue life studies of various metals have shown that there are two distinct phases in the history of a fatigue failure: the crack initiation phase and the crack propagation phase. The crack initiation phase normally takes many more cycles than the propagation phase; however, some weld-related stress concentrations are so high that they virtually eliminate the initiation phase and permit cracks to begin growing very soon after the service loads are applied (see Figure 3) (8). Obviously, this dramatically shortens the life of the machines and structures in which such welds occur.

Weld Toe Grinding

There are several techniques listed in Figure 1 that can substantially improve the fatigue strength, and thereby the fatigue life, of as-deposited welds. One of those techniques is grinding the toes of the welds. Two distinct types of grinding tools have been tested: disc grinders and burr grinders. The primary point of this method is to create a better weld angle and/or a better toe radius. The grinding methods under consideration here can improve both aspects of the weld geometry. Figure 4 (9) illustrates the benefits of both methods by comparing as-welded fatigue strength to that of ground welds. The results are better for the burr ground welds – probably because the grinder is easier for the operator to control. The burr grinding technique is illustrated in Figure 5. The most significant improvement from this technique is probably related to the removal of welding-induced geometry and flaws near the weld toe; typical weld defects such as cold lap and undercut can be completely removed by these methods. Changing the weld toe radius from 0.004 inches to 0.100 inches improves the worst case stress concentration in the range of parameters mentioned above from 2.6 to 1.3.

Tungsten Inert Gas (TIG) Re-melting

One of the most beneficial fatigue life improvements available is the technique of re-melting the weld toe using a TIG torch (used in gas tungsten arc welding) with no filler metal. This is illustrated in figure 6. The TIG torch is slowly worked along the length of the weld to create a small re-melted area at the weld toe. This procedure eliminates many common weld defects by simply melting them and it forms a better weld angle and toe radius. Figure 7 (10) shows the fatigue strength improvement that is achieved in a mild steel. It is worth noting that the beneficial effects of this treatment extend into the low cycle fatigue range. This technique may also be applied using a plasma welding torch with no filler metal. The results for plasma re-melting are slightly better than TIG due to its higher heat input. These re-melting techniques provide fatigue life improvements comparable to burr grinding in mild steel and considerable improvement in high strength steels (see figure 8) (11).

Residual Stress Improvement

Welding any two components together develops significant residual stresses; this is a direct result of the contraction of the weld upon cooling (see figure 9). In many cases, the residual stresses in the vicinity of the weld – for some portion of the length of the weld - approach the yield strength of the weld or parent metal; this is especially true in the area at the weld toe where stress concentrations due to the local geometry are normally quite high. When the welded structure is subjected to service loads, the service stresses are superimposed on the residual stresses, often developing stress states at the weld toe that were not accounted for in the design of the structure. In those locations where the residual stresses are at or near the yield strength, any fluctuating loading that produces a tensile stress will result in a stress-strain cycle that contains elastic and plastic strain components. Repeated plastic cycling leads to rapid crack initiation and failure.

Reduction of these harmful, tensile residual stresses is an effective fatigue life enhancement, especially in the high cycle life regime.

Thermal Stress Relief

One of the simplest methods of reducing residual stresses is to heat the welded structure to a temperature at which the yield strength of the structural materials and the weld filler materials is well below room temperature values. The residual stresses are “relieved” as localized plastic deformation takes place. This method of dealing with residual stresses is effective, even though it only lowers the value of the tensile residual stresses. ASTM A-514 is a typical structural steel with a specified minimum yield strength of 100 ksi at room temperature. Stress relief procedures for this steel call for the relieving temperature to be above 900°F and below the tempering temperature (normally around 1150°F to 1200°F). At 1100°F, the yield strength of this material will be in the range of 40 ksi to 50 ksi. When the welded assembly is returned to room temperature, the residual stresses will be in the range of 40% to 50% of the room temperature yield strength, as compared to 100% of the room temperature yield strength prior to the thermal stress relief procedure. Researchers have established that lowering tensile residual stresses at the surface of welded structures results in increased fatigue life, and that thermal stress relief lowers residual stresses (3). In some cases, the completed size of a welded assembly can make thermal stress relief of the entire structure impractical or impossible. In such cases, it may be possible to apply localized stress relief to only the welded joints; this type of local stress relief has been successfully applied to field construction and repairs of critical pressure parts in steam piping and pressure vessels for many years.

Vibratory Stress Relief

The underlying principles of this method are not well understood, even by those who are its staunchest advocates. The evidence for its usefulness is primarily anecdotal, and there is published research showing that postweld vibratory stress relief has little to no effect on residual stresses (3); however, there is enough evidence to warrant further investigation. The method consists of using a mechanical shaker connected to a variable frequency waveform generator. The shaker is connected to the part that requires stress relief, and the part is then vibrated at substantial amplitudes over a range of frequencies until a low mode, high response resonance is identified. The shaker is tuned to a frequency just below the resonant peak and vibrated until a noticeable shift occurs in the resonance; this shift is the “proof” that the desired stress relief has occurred. Although a number of manufacturers have reported longer lives for their welded parts after using this method, caution should be exercised before assuming that this method may be successfully applied to a specific welded structure.

Shot Peening

The shot peening process uses small diameter iron shot, cut steel wire, or ceramic or glass beads which are propelled at high velocities (up to 200 ft/sec.) against the surface of the part to be treated. Because the shot media creates small craters or dimples on the surface by localized plastic deformation of the surface, it leaves a thin layer of residual compressive stress at the surface of the treated part. These residual stresses are around 60% to 75% of the tensile strength of the treated metal, depending on the initial hardness of the treated part (see Figure 10) (12). There are two standard parameters used to gauge the effectiveness of shot peening treatments: the Almen intensity and the surface coverage. Almen intensity is measured by the curvature of standardized metal strips exposed to the same peening treatment as the surface of the treated part; these strips bend due to the plastic deformation on the exposed side of the strip and the amount of bending is carefully measured (see Figure 11) (12). The surface coverage for small areas is gauged by visual examination of the part at 10X magnification; for larger areas, the surface is pre-treated with a fluorescent dye which is removed during the peening process; the 10X examination is then performed using a black light to reveal any under-peened portion of the surface.

This type of surface treatment has proven very effective in changing the residual stress patterns created by welding and thereby increasing the fatigue strength of welded assemblies (see Figure 12) (12).

Hammer Peening

Hammer peening is a manual process that uses pneumatically or electrically driven tools to create residual compressive stresses by plastically deforming the surface of the treated part. The most commonly used pneumatic tools deliver around 80 blows/second and use semispherical, hardened steel tips. Hammer peening of welds is accomplished by working the tool along the toe of the weld at a rate of around 1 in./sec. Researchers have found that this technique requires four passes to achieve optimum results. This type of peening can be done using a standard pneumatic chipping hammer with a modified tool tip.

Another variation of this method employs an ultrasonically driven hammer capable of about 27,000 blows/sec. The tool travel speed along the weld is around 18 in./minute, but the treatment only requires one pass.

The depth of compressive residual stress from hammer peening is substantially greater than that from shot peening, resulting in higher fatigue strength. Hammer peening, and particularly ultrasonically driven hammer peening, produces some of the greatest fatigue strength improvements over the as-welded condition of any improvement method (see Figure 13) (13). Some investigators report that ultrasonic hammer peening is so effective that the fatigue initiation sites in their experiments move away from peened weld toes to other locations in the specimens (14).

Practical Considerations

Some of the most effective methods mentioned above require little, if any, additional equipment or skill beyond that which would ordinarily be present in a typical welding shop. Shops that employ gas tungsten arc welding as one of their ordinary welding practices will have little difficulty performing the TIG weld toe dressing described above. Nearly all welding shops use power tools to remove welding flux; these tools can usually be refitted with the kinds of tool tips that will be effective in hammer peening welds. Most welding shops have pneumatically or electrically powered grinding tools used to clean and dress fabricated parts. Disc grinders are more common than burr grinders, but these tools are relatively inexpensive, as are the consumable burrs and discs that are used to grind weld toes.

Each of these methods requires some amount of operator training, but this is minimal for the TIG dressing, weld toe grinding, and hammer peening techniques. In these cases, the labor to treat the welds is far more expensive than the tooling – especially if the tooling is already in the possession of the welding shop. The cost of labor to perform these improvements might lead to some consideration of which welds should be treated. This requires additional design work to identify the welds that require postweld treatment to extend the life of the fabrication.

The other methods, thermal or vibratory stress relieving, shot peening, and ultrasonically driven hammer peening, each require equipment not ordinarily found in welding shops; and some require special training as well. However, there are advantages to some of these methods: shot peening can cover a large surface area more economically than hammer peening; ultrasonically driven hammer peening generates much less operator fatigue and shop noise than pneumatically driven hammer peening; thermal stress relief provides a through-thickness treatment whereas the other methods are primarily surface treatments. If a welded assembly is placed in service where a high rate of corrosion or erosion is expected, the surface treatments might be rendered ineffective by those conditions.

Summary

This paper has considered several of the most commonly available fatigue strength enhancement techniques for welds. Most of these methods have been proven by research and by experience to be beneficial in improving the fatigue strength and therefore the fatigue life of welded parts. Some of the most beneficial methods employ skills and equipment that are readily available in welding shops.

Acknowledgements

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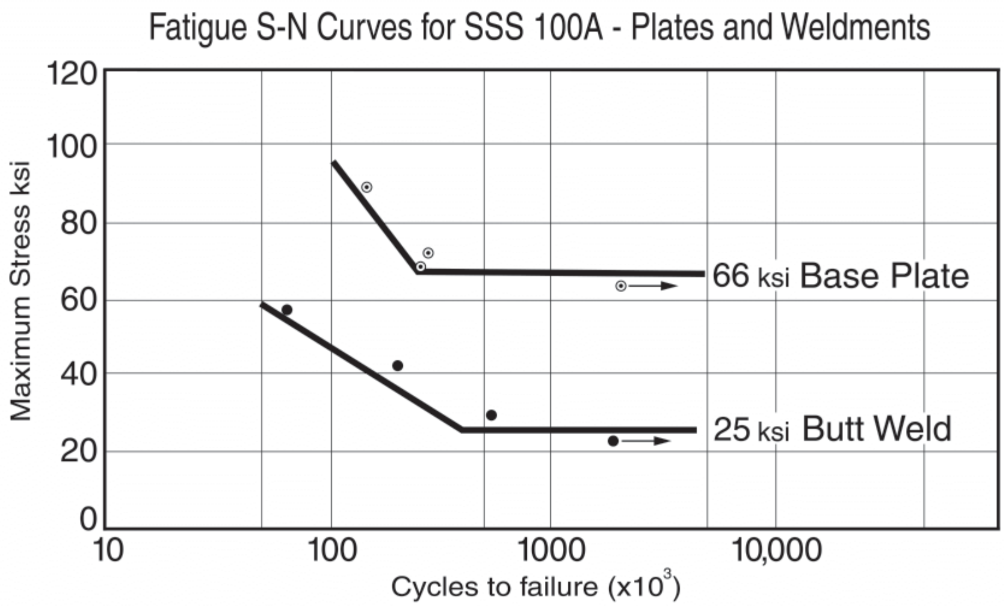

Figure 2

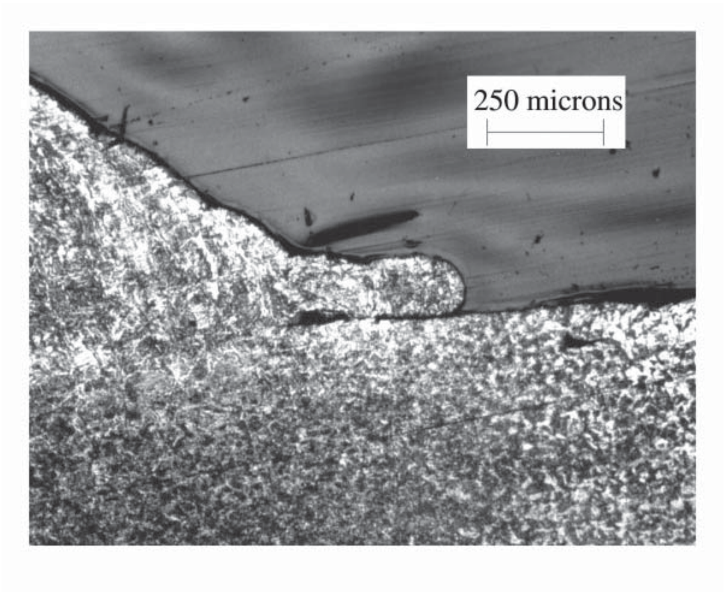

Figure 3 - Cold Lap

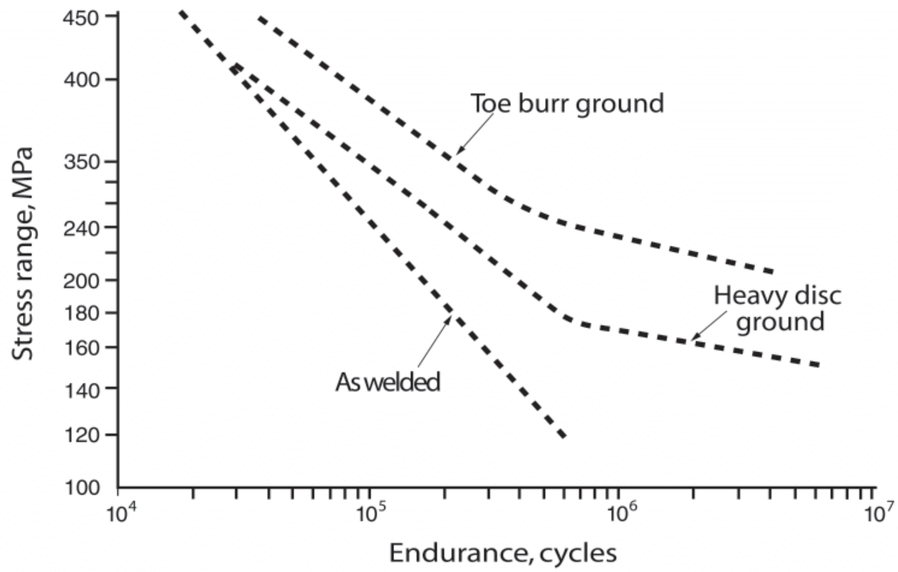

Figure 4 - Effects of Grinding

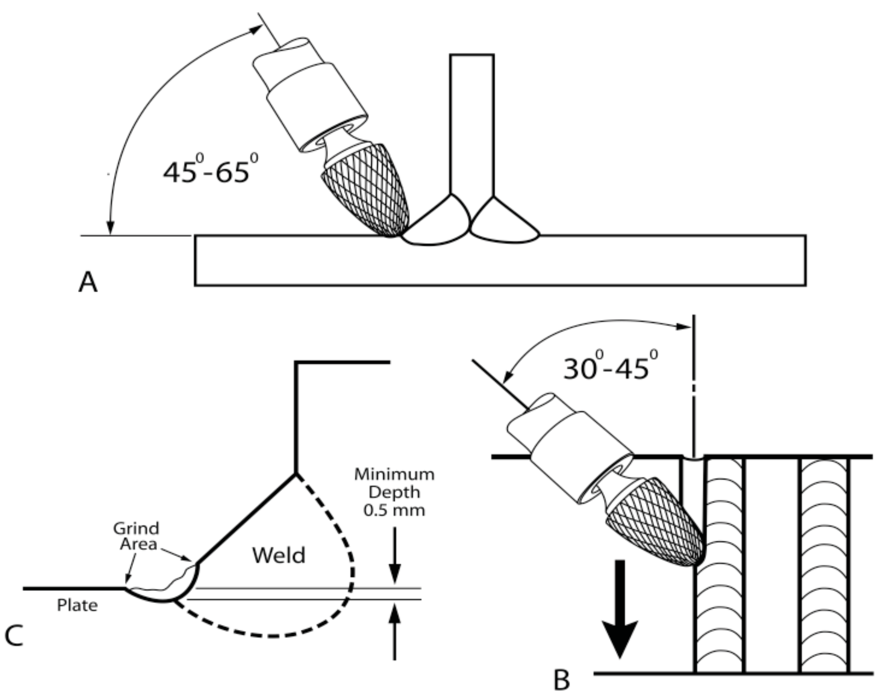

Figure 5 - Burr Grinding

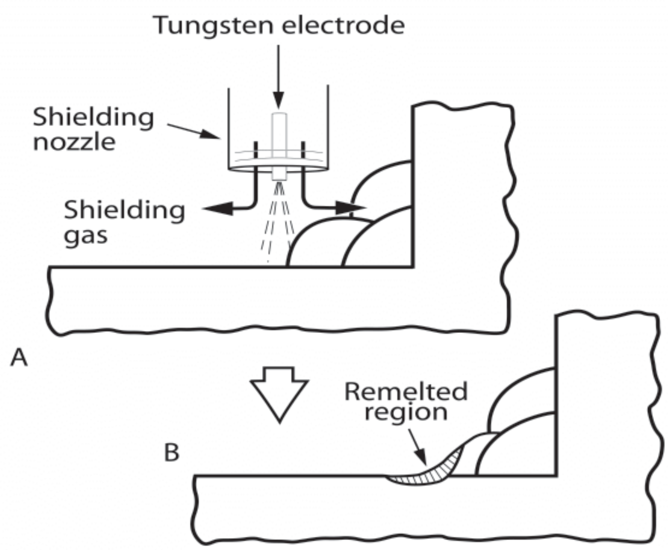

Figure 6 - TIG Re-melting

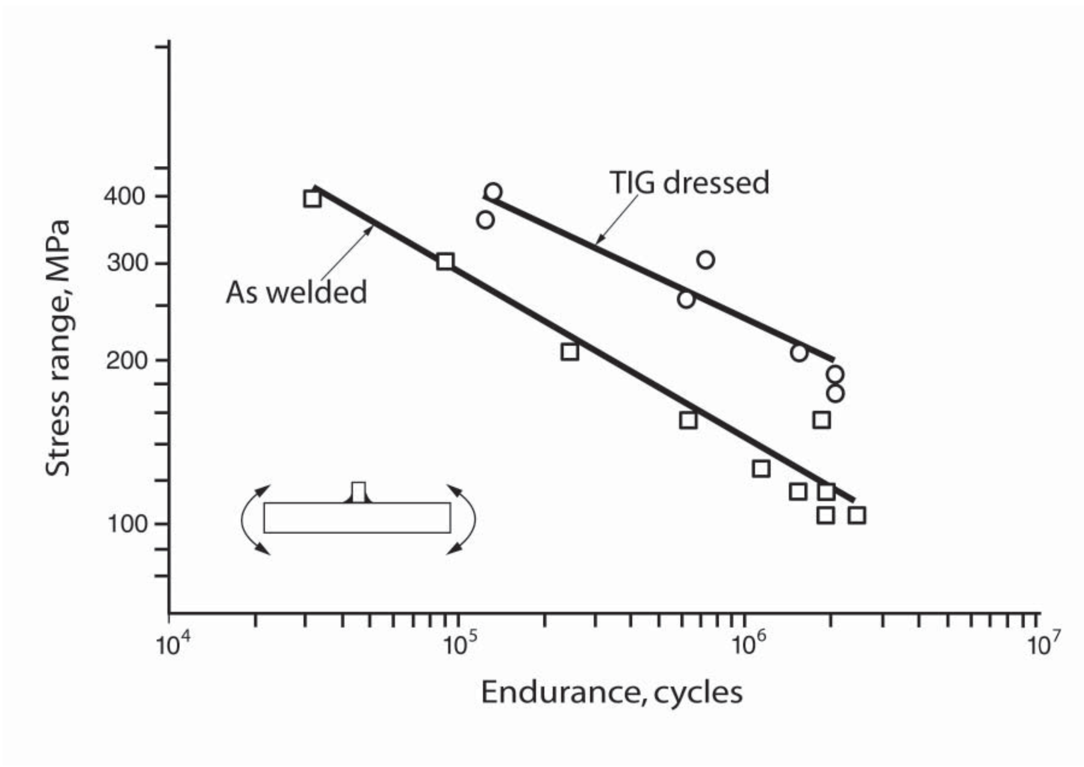

Figure 7 - Effects of TIG Re-melting

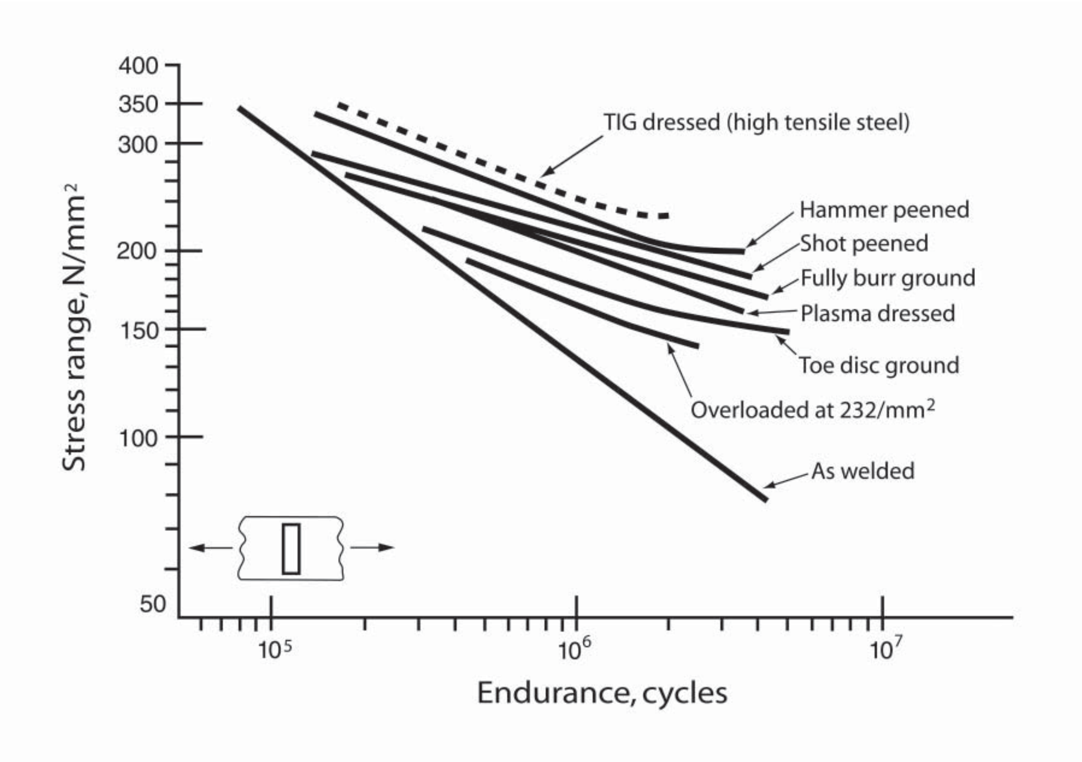

Figure 8 – Comparison of Effects

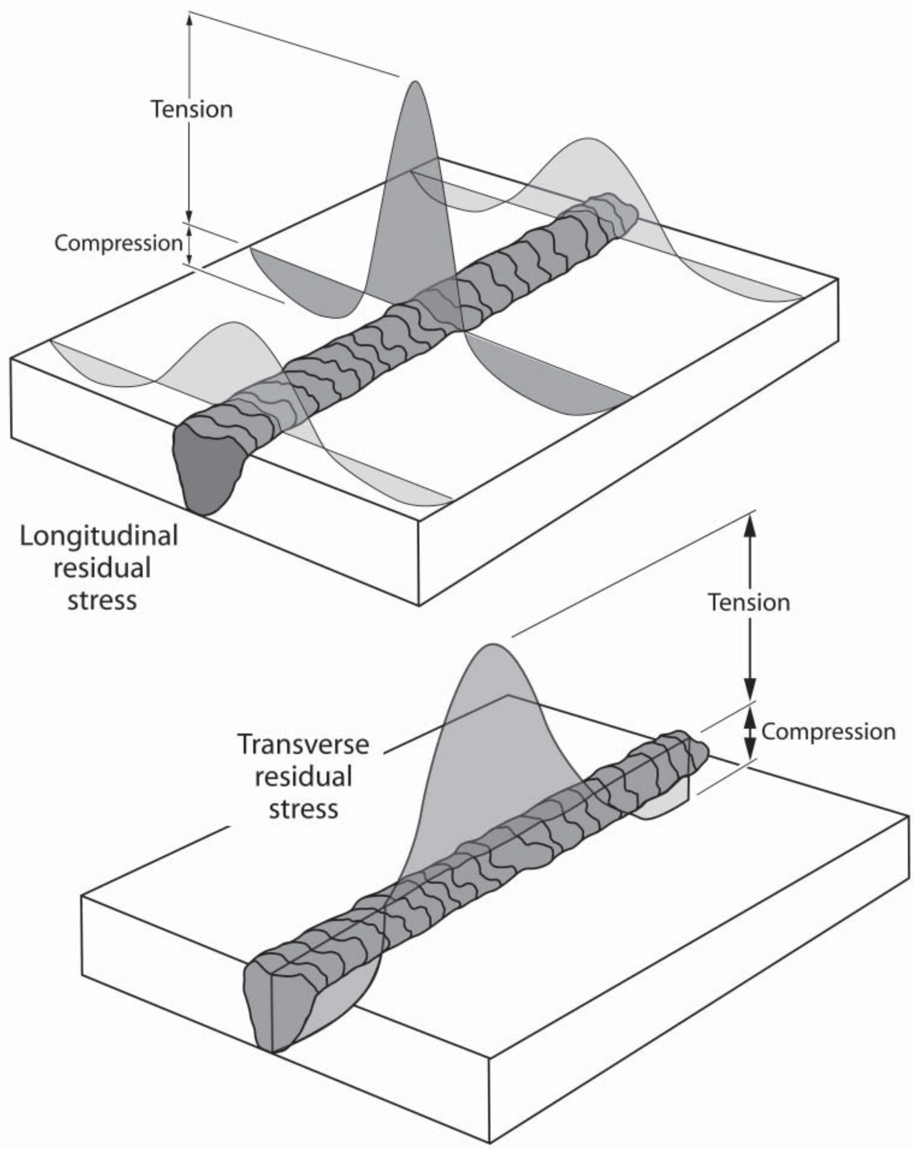

Figure 9 - Residual Stress Distribution after Welding

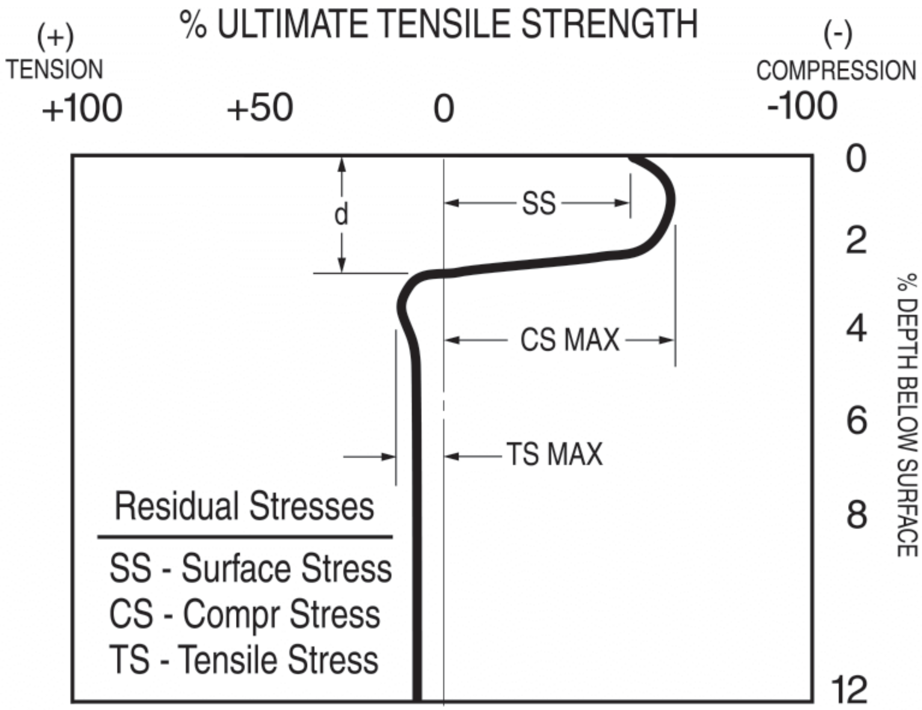

Figure 10 - Residual Stresses after Shot Peening

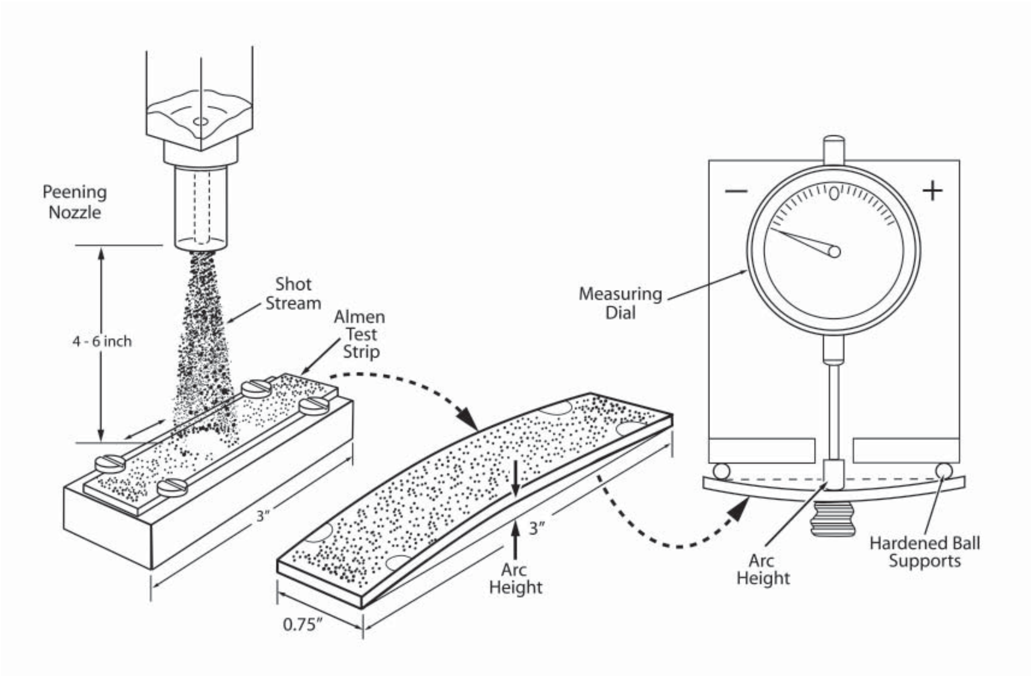

Figure 11 - Shot Peening Effectiveness

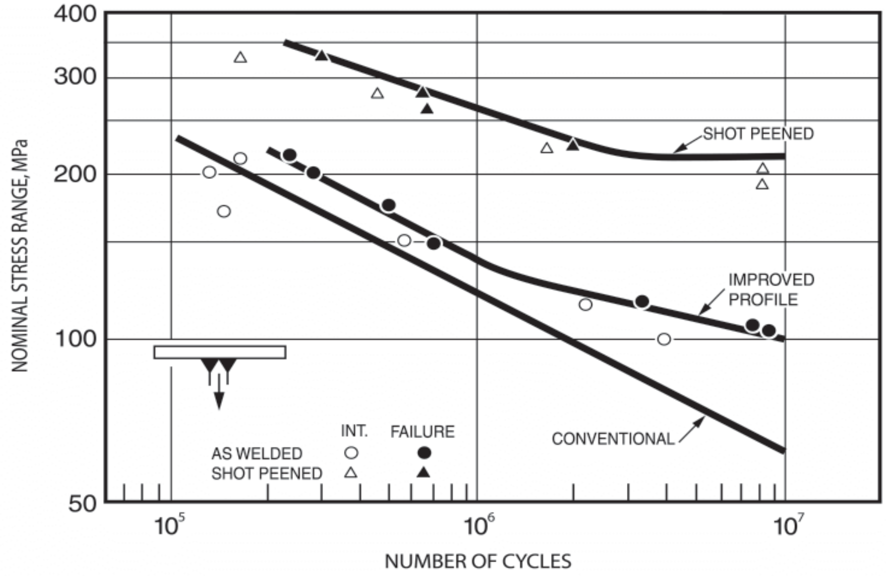

Figure 12 - Effects of Shot Peening

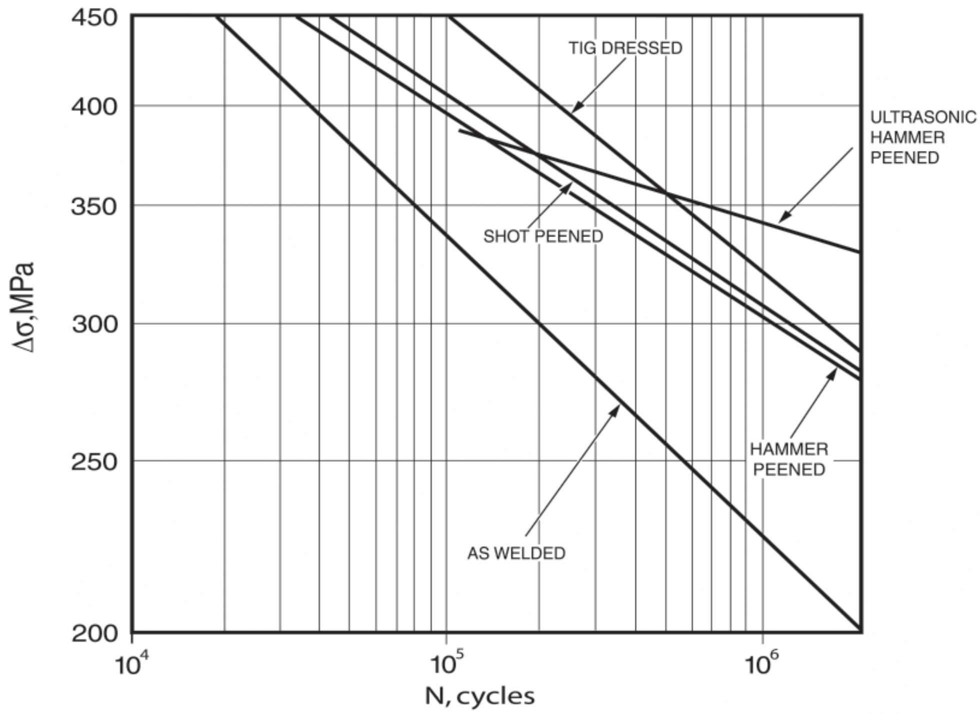

Figure 13 - Comparison of Effects - HSLA Steel