Inspecting for Fatigue

Simple inspection techniques can reveal fatigue cracking while weld-repair is still possible

BY J. E. JONES

Proper welding technique, procedure, and consumable selection are quite important to successful repair of heavy equipment. However, if the elusive fatigue crack propagates too far without being observed, then disaster may occur, despite the best efforts of the maintenance engineer, foreman and repair crew. By using appropriate inspection techniques, fatigue cracks can often be detected and repaired before the strength or stability of a piece of heavy equipment is degraded below minimum requirements for service. In addition, errors or oversights in design or manufacturing which produce potential sites for initiation of fatigue cracking can be identified and modified or repaired before fatigue cracking has a chance to get started.

When looking for fatigue damage, two things are required. First, the observer needs to have a basic understanding of the principle of fatigue, which differs significantly from overload failure. Second, the use of appropriate inspection procedures and techniques will substantially increase the probability of detecting fatigue damage.

This article will first review briefly the principles of fatigue; then, a discussion of inspection techniques and procedures will be presented. The information discussed here is derived from several sources; works consulted are listed at the end of the article. In addition, the author has drawn on his own experience as a metallurgist and consultant.

Principles of Fatigue

Fatigue damage to materials has been recognized as a potential failure mechanism of welded assemblies for many decades. Any structure that is subjected to repeated loading may be a candidate for a fatigue failure. The frequency of loading, in general, has very little influence on the susceptibility to fatigue; thus, an above-ground pipeline that is stressed daily by the heating of the sun, a dragline that may be loaded only once each few minutes, and an engine mounting that is loaded by each revolution of the engine, several times per second, may all experience fatigue damage. Equipment is also subject to fatigue failure, even though the applied loads are well below those that the material should be able to withstand easily.

It has been shown that fatigue cracking will, nearly without exception, initiate at a surface and propagate in a direction perpendicular to an applied tensile load. Thus, those inspection techniques that are used to find surface flaws are usually quite applicable for detecting fatigue damage.

Metals possess a characteristic strength, called the elastic limit. When stressed below that level, they will return to their original shape; if stressed above that limit, they will experience permanent deformation known as plastic yielding. Generally, when an overload failure occurs, a large deformed, or strained, region will appear before final rupture. However, unlike an overload failure, fatigue cracking occurs with loads much lower than the elastic limit of the material. Because of this lack of deformation, fatigue cracks are exceedingly difficult to see, particularly in the initial stages of crack growth. In addition, the slow incremental growth of fatigue cracks, since it is not characterized by large strain or loud noise, may go undetected by the operator of a machine who has been working well within the load limits for his equipment.

Data that can be used to predict fatigue behavior of metals is usually presented in the form of an S-N curve. These curves are taken from a number of laboratory tests, each conducted with a different mean or maximum stress. The number of cycles to failure is plotted versus the stress level for the test. Figure 1 is an example of such an S-N curve.

The Notch Effect

Theories of fatigue crack initiation have shown that plastic (permanent) deformation of the material must occur before fatigue cracks can start. But, as stated above, it is well known that fatigue damage will occur in materials at applied loads much below those required for plastic yielding. The reason for this apparent anomaly is that a notch in the surface of a member exposed to stresses much below the yield point will serve to concentrate that stress. Thus, even though the cross-sectional area of the member is not reduced appreciably, the concentrated stresses at the root of that notch may, easily, be several times greater than the applied stress, resulting in localized micro-yielding at the root of the notch.

This effect of notches gives the best clue to the most likely location for fatigue damage to occur. Any scratch, gouge, nick or deliberately machined notch is a likely candidate for initiation of a fatigue crack. Examples of these would include keyways in axles, gears, sprockets and pulleys, the toe of a weld, or incomplete fusion at the root of a weld.

This notch effect is illustrated well by the S-N type curves shown in Fig. 1. An AISI 2340 steel, heat treated to Rockwell hardness of C-48, is tested in fatigue. As can be seen in the figure, the notched specimens failed, due to fatigue, in the same number of cycles but at substantially less applied stress than the unnotched samples.

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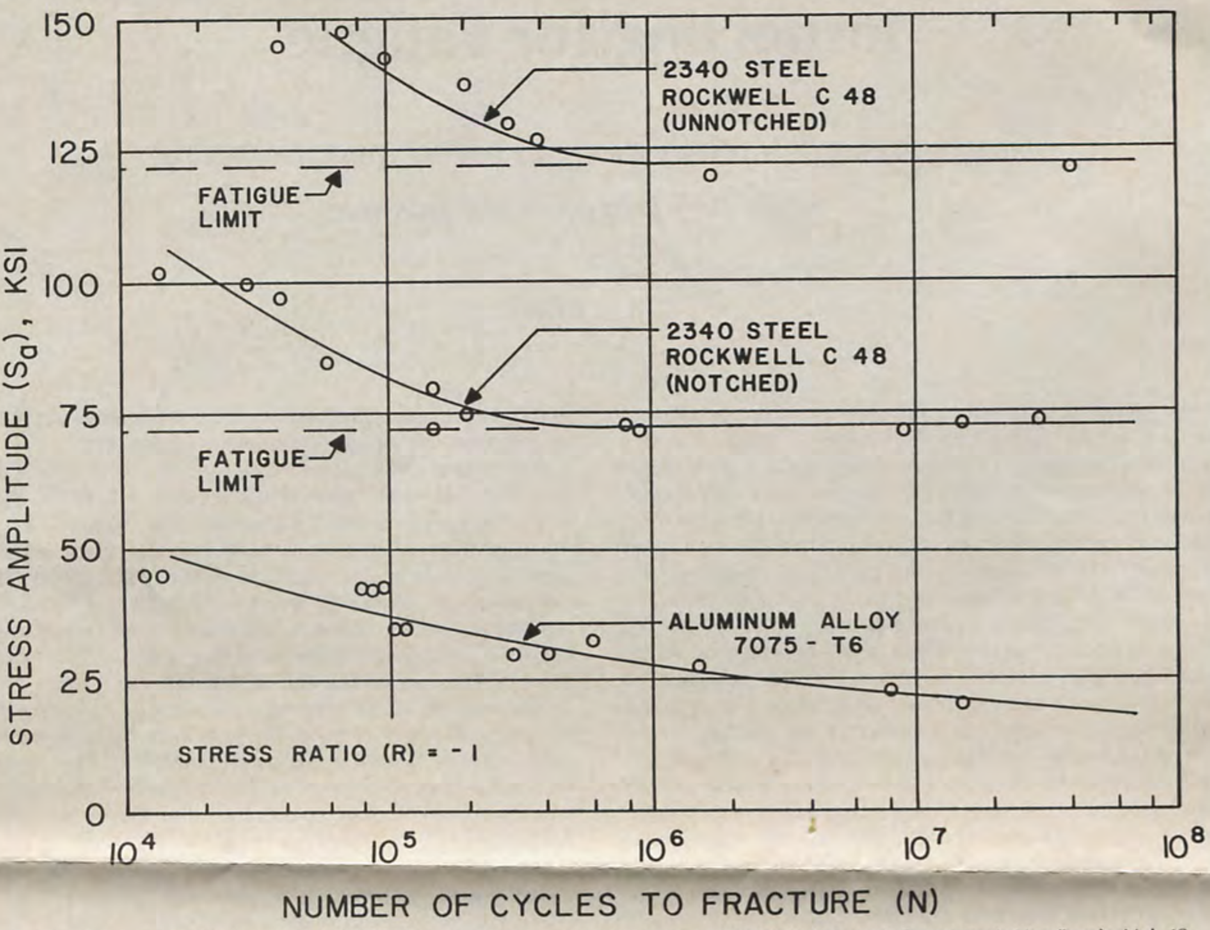

Fig. 1—S-N curves of fatigue data for 7075-T6 aluminum, and notched and unnotched 2340 steel. From Metals Handbook, *Vol. 10, 8th Edition, "Failure Analysis and Prevention." Published by the American Society for Metals*

The Fatigue Limit Effect

The theory of fatigue crack initiation also suggests that fatigue damage depends not only on plastic deformation, but also on the particular material. For certain materials with a particular strength and thermomechanical processing history, there is a stress below which fatigue will not occur. Although many factors may affect the "fatigue limit" mechanism, we need only be concerned with the outcome of this fatigue limit phenomenon. Thus, even though some plastic yielding may occur at the tip of a notch, if the stress is insufficient to cause fatigue, then no fatigue crack will initiate, no matter how many stress cycles are experienced by the member.

This is also illustrated in Fig. 1. Both S-N curves for 2340 steel indicate that an increased number of cycles are required to initiate fatigue damage as the mean applied stress decreases from a maximum value. However, once the mean applied stress is reduced below a certain point (called the fatigue limit) fatigue failure is not observed. The existence of a fatigue limit is only observed in certain materials, primarily in ferrous materials such as steel. As can also be seen in Fig. 1, 7075 aluminum in the T6 condition will experience fatigue damage even at very low mean applied stress if the number of fatigue cycles is sufficiently large; this material has no fatigue limit.

This fatigue limit effect can be a significant factor in establishing an inspection program for heavy equipment. Whenever equipment use is changed, the inspection program should reflect those changes. For example, a dragline which has been operating to remove overburden from a coal seam is moved to a different location. Several changes could occur which may not be recognizable, but which can be significant. The machine may not be exactly level and the direction or degree of tilt may be altered, the overburden rock type may be changed, or the direction of movement to the dump site may be reversed. Any one of these new operating conditions may change the overall stress distribution in the load carrying members of the equipment, and will probably change the stress experienced by any given part of the machine. A notched member which, prior to the move, experienced loads below the fatigue limit may now be stressed above that limit, and may begin to experience fatigue damage.

A change in operating condition of any equipment must be accompanied by a change in inspection program. Parts of the machine which never before had needed repair may need constant attention following a change in operating situation. In addition, some changes in operation of a machine may go undetected or unnoticed. Consequently, a comprehensive inspection program must include not only those portions of the equipment which seem to require constant repair, but also periodic checks of all the stressed members in the machine.

The Residual Stress Effect

One ingredient which is essential for fatigue cracks to initiate is a tensile stress on the surface of the material. If a member is cyclically compression loaded, or if for some reason the surface is never stressed in a tensile mode above the fatigue limit, fatigue cracks should never appear. Although applied loads are responsible for the occurence of fatigue damage, if residual stresses are present they may significantly alter the response of the material to fatigue loading.

The surface of a weldment is often in a state of residual tensile stress following the welding operation. An applied tensile load will add to this residual stress, causing the stress on the surface of the weld to be greater than the overall applied stress. Even though the applied load results in a bulk stress level below the fatigue limit, the surface of the weld may be experiencing cyclic stresses far in excess of the fatigue limit.

Failure of welds in fatigue can occur from internal discontinuities; however, in most cases, a fatigue failure of a weld will occur because of an external geometrical notch. The failure will probably initiate at the toe of the weld reinforcement or the root of a weld with an inadequate joint penetration (I-P) defect. Fatigue damage occurs in two stages: an initiation stage during which the tiny beginning crack is formed, and a propagation stage during which the crack grows in steps with each load application until the remaining load carrying cross-section is insufficient to carry the applied load and final rupture occurs.

In some cases, an I-P defect will be associated with a crack that formed due to residual stresses. When such a weld is cyclically loaded, that crack can immediately begin to propagate. Since the initiation period of fatigue damage may be a large share (as much as 50%) of the total life of a member, an I-P defect will substantially decrease the life expectancy of a welded structure.

Inspection Methods

Virtually all NDE methods can be used to detect fatigue damage. However, certain methods are best suited to particular applications. In addition, the cost and difficulty of using a particular method must be weighed against the utility of using it. The following is a discussion of some of the most popular inspection techniques, including some relative cost information.

It is difficult to establish rules for choosing the appropriate technique for any application. Many variables must enter into the decision, such as the on-site or nearby availability of the required equipment, the cost of the inspection, and the ability of inspectors or maintenance personnel to interpret the results and data from an inspection. These factors are just as important as the applicability of a particular method to a specific configuration of equipment.

Visual Inspection

The most utilized method for detecting fatigue damage is simple visual observation. However, it is impossible under most circumstances to inspect an entire piece of equipment with a magnifying glass or a microscope. A good maintenance inspector will look carefully at the entire machine, but will only give a detailed inspection to certain identifiable areas.

The first key to determining a likely region for fatigue damage is the notch effect discussed above. The existence of any abrupt change in cross-section of a member will produce the notch effect. Visual inspection for the effect of fatigue must include all areas of abrupt change in surface contour of a member. Examples of such likely fatigue areas include: the toe of a weld, areas of incomplete fusion, bolt holes, surface irregularities caused by oxygen cutting, or the irregular surface of a weld bead.

The notch effect may also be present because of surface conditions. For example, wear scars or fretting due to metal-to-metal contact may create a notch. An important consideration which is often overlooked is that many corrosion processes, especially pitting corrosion, may cause an irregular surface or notch from which a fatigue crack can initiate.

In laboratory testing, researchers often coat a sample with a brittle plastic, which will develop small cracks to show areas of high strain. Paint can often be used for the same purpose on heavy equipment. A fatigue crack may be tightly closed and difficult to find in bare metal. Since a small plastically deformed region has been pushed ahead of the crack tip, paint may crack or spall off of that region, indicating the presence of the crack. Visual inspection should note areas of cracking and spalling paint or areas of rust stains where small micro-cracks in the paint have allowed moisture to enter and attack the metal surface. Paint wear can also be used as a good indication of wear scars that may be notches for fatigue crack initiation. Paint will usually blister or develop a rough or irregular texture wherever corrosion is occuring. These areas should be cleaned and inspected for possible fatigue damage before repainting is done.

Visual inspection, while not employing complicated or expensive equipment, may often yield excellent results in the detection of fatigue damage. Visual observation can often be accomplished without costly shutdown of equipment, and it requires little training. In fact, equipment operators can easily inspect many potential areas for fatigue damage and report irregularities to maintenance personnel on a daily basis. This can decrease the required number and frequency of maintenance inspections and increase the likelihood that a fatigue crack will be detected and repaired before reaching a critical size for catastrophic failure.

Dye Penetrant And Magnetic Particle Inspection

Although visual inspection can often detect fatigue damage, a fatigue crack, particularly in the early stages, may be tightly closed and nearly impossible to see. However, with the use of magnetic particles or dye penetrants, those tightly closed cracks can become apparent.

The technique for magnetic particle testing requires that an electrical current be run through the part being inspected. This current will generate a magnetic field, the effects of which can be seen by sprinkling iron powder on the surface. Irregularities in that magnetic field caused by fatigue cracking will be observed as lines or patterns in the arrangement of the iron powder. Thus, cracks which may not be visible to the unaided eye become readily apparent with magnetic particle testing.

Any conducting material can be examined using this method, and the equipment is not very expensive. However, there are certain drawbacks which must be considered. First, the member must be accessible to attach the electrodes. Second, stray magnetic or electrical fields generated by the primary current may interfere with the operation of the equipment being inspected. Consequently, a shutdown may be required for a magnetic particle inspection. Finally, any irregularity in the surface contour of the part will result in a disturbance of the magnetic fields so that a notch may, itself, cause the magnetic particle inspection to indicate the presence of a crack, whether one exists or not.

Dye penetrant techniques can also indicate the presence of a crack. Although this method is generally less sensitive to the presence of a crack, it is easier to use, does not need any special equipment, and usually does not require the shutdown of the machine. Penetrant testing is done by first cleaning the surface to be inspected and then spraying on a thin coating of liquid dye. The liquid dye will seep into any fatigue cracks, and will not be removed from those cracks when the surface is cleaned the second time. Finally, a white powder, called the developer, is sprayed on the surface and will absorb some of the dye trapped in the fatigue cracks and stain. Even better resolution of these cracks is obtained by using a dye that is sensitive to ultraviolet light; when a UV light source is used to illuminate the developer, any absorbed dye is easily seen.

Dye penetrant inspection is particularly useful for detecting surface flaws such as fatigue cracks. However, it may be difficult to clean the dye from an irregular surface, and the irregularities will then appear as stains in the developer. These stains may be erroneously recorded as cracks, or may mask the presence of fatigue damage. Nevertheless, due to the ease of application and relatively low cost, dye penetrants are used quite frequently and successfully to detect fatigue damage.

Radiographic Inspection

Radiography is based on differential absorption of penetrating radiation in the form of x-rays, gamma rays or neutrons. Since neutron radiography requires specialized equipment that is not usually available, only x-radiation and gamma radiation will be discussed here.

In conventional radiography, the part to be inspected is illuminated by an x-ray tube or a gamma ray source. Whatever radiation is not absorbed impinges on a film, resulting in a two-dimension[illegible]age of the internal structure of the part. Any regions such as porosity or a crack which do not absorb radiation will leave a dark area on the film. In general, radiography can only detect discontinuities that have a substantial thickness in the direction parallel to the x-ray beam. Consequently, planar discontinuities such as fatigue cracks, can only be detected if the radiation beam is properly oriented with respect to the crack.

Radiography has only limited applicability in detection of fatigue cracking, because of the orientation problem. In other words, if enough is known about the crack to properly orient the x-ray beam, it can probably be detected without the use of radiography. In addition, radiography has several other drawbacks. It is relatively expensive in comparison to other inspection techniques, with up to 60% of the total inspection time being spent on set-up. Due to the health effects of penetrating radiation, the shielding of workers and operators may also be costly and time consuming and will probably require substantial downtime for the equipment being inspected. Finally, the member being inspected must be accessible from both sides for the placement of the source and the film.

Ultrasonic Inspection

Ultrasonic inspection is much better suited to detecting fatigue damage than radiography. The use of ultrasound requires that a transducer be swept over the surface of the member being tested. The transducer generates pulses of high frequency acoustic energy (like sound waves, only at frequencies much above the human hearing range). These acoustic pulses are reflected from boundaries within the material. If no boundaries are encountered by the acoustic pulse, it is "echoed" back to the transducer by the back side of the member. Planar discontinuities such as fatigue cracks are easily detected by the presence of these reflected pulses. In a simple "A scan" the reflected pulses appear as "blips" or peaks on the oscilloscope display screen of the ultrasonic equipment. More sophisticated (and more expensive) equipment can produce displays of two dimensional images of the flaws in a member (a "B scan"), or displays which define the three-dimensional picture (a "C scan").

Ultrasonic inspection requires access to only one side of the member being inspected and, although the equipment can be relatively expensive to purchase, it can be portable and easily used in the field. However, a relatively skilled technician is required to operate the equipment and to interpret the results of an inspection; this requirement, coupled with the equipment cost, may make it difficult for an individual company to do its own in-house ultrasonic inspection. Fortunately, there are field inspection services available at a reasonable cost from many vendors, and the work is generally of high quality since the vendor technicians are usually well-trained and experienced in use of the equipment.

Conclusions

1. Although many nondestructive testing techniques can be used for detection of fatigue damage in heavy equipment, visual inspection is the most widely applied method. It can be quite successfully used to find propagating fatigue cracks in regions of likely fatigue damage.

2. To apply any inspection technique properly, a basic knowledge of fatigue principles is required. Maintenance personnel as well as operators can detect fatigue damage and initiate repair procedures early to prevent catastrophic failure if the principles of fatigue are understood and used to identify likely areas for fatigue damage.

3. Following a visual inspection, dye penetrant or magnetic particle testing can be used to better identify fatigue damage or for detailed inspection of suspect areas.

4. Radiography can be used to inspect for fatigue cracking. However, radiography requires careful alignment, heavy screening, and a substantial investment of money, time and skilled personnel, which makes it less attractive than other NDE methods in this application.

5. Ultrasonic inspection can detect fatigue damage which cannot be found using visual observation, dye penetrant inspection, or magnetic particle testing. Discontinuities can be detected in regions that are not accessible for visual observation. Drawbacks include: a) relatively high cost, b) requirement for skilled operators, and c) a need for trained technicians to interpret the data.

Works Consulted

Dieter, G. E. *Mechanical Metallurgy*, 2nd Edition. McGraw-Hill, 1976.

Gurney, T. R. *Fatigue of Welded Structures*, 2nd Edition. Cambridge University Press, 1979.

Fatigue of Welded Steel Structures. Welding Research Council, 1964.

Fatigue Testing of Weldments, STP 648. American Society for Testing and Materials, 1977.

Metals Handbook, Vol. 10, 8th Edition, "Failure Analysis and Prevention." American Society for Metals, 1975.

Metals Handbook, Vol. 11, 8th Edition, "Non-destructive Testing and Quality Control." American Society for Metals, 1977.

Reed-Hill, R. E. *Physical Metallurgy Principles*, 3rd Edition. Van Nostrand, 1978.