Dyescan Tracers as a Quality Control Tool for Coverage Determination in Controlled Shot Peening

1985006

Peter O'Hara

Metal Improvement Company, Inc.

Newbury, United Kingdom

ABSTRACT

The Shot Peening process is not new, but like most forms of technology, its application and development has accelerated in recent times by greater knowledge of what is happening at and beneath the surface and how the process should be applied. It has become clear that the uniformity of surface indentation is critical to achieving the best increase in fatigue strength and on production, maintaining that degree of cold work on subsequent parts once the parameters and acceptable life are established. The accepted method of determining uniform complete indentation or coverage is by visual means using a 10-power magnifying glass. However, it is difficult and time consuming to visually examine large areas, hardened steel parts, fillets, cavities, grooves or holes with that glass since many areas are inaccessible to visual instrumentation. A recent development is the use of Dyescan Tracers which compliment the 10-power glass and are applied before peening to form a thin brittle film which breaks up under the action of peening. An ultra-violet (U.V.) light is then used to examine for coverage with fully peened areas appearing deep purple and partially peened areas appearing white, or speckled white.

THEORY OF SHOT PEENING

IT IS ESSENTIAL to understand what the process is about before it can be appreciated why the controls of the application are so critical. Fatigue, fretting or stress corrosion failures tend to result from surface tensile stresses, whether applied or residual from manufacturing operations. The ability to negate those tensile stresses by the generation of a residual compressive stress can prolong life considerably. This is achieved by cold working the surface with small spherical particles travelling at high velocity. Each particle on impact deforms the surface which induces a compressive stress. This is shown in diagramatic form in Figure No. 1, where the high magnitude compressive stress is balanced by a low magnitude tensile stress beneath the surface. Figure No. 2 shows the effect of a single indent, in this case with a 6.4 mm. ball, on mild steel. The large grained (white) area is the zone of plastic flow with the maximum compressive stress at the surface within the 1,25mm. diameter. The stress pattern at the centre of the indent through to the core is as shown in Fig. No. 1 (A). A similar profile exists on the surface from the edge of the 1.25mm. indent stretching out radially with the result that each single indent has a hoop tensile stress at the surface at the perimeter of the worked layer. A peened surface with overlapping dimples has a uniform stress profile, as shown by Fig. No. 1 (A) over the complete fatigue critical area.

The depth of the compressive layer varies with a number of factors and generally is 0,05mm. to 1mm., although greater depths can be achieved on certain materials. Figure 3 shows the depths possible at different hardnesses and Almen intensities. The Almen intensity being an indication of the kinetic energy transfer of the peening action which will be explained later.

The magnitude of compressive stress generated is approximately 60% of the ultimate tensile strength of the material and is shown in Fig. No. 4. Therefore, from Figs. 4 and 5 it will be seen that the higher the tensile strength/hardness, the lower the depth of compression at the same intensity, but the greater the magnitude of compressive stress. Demonstrating that although shot peening can be used on low carbon steels with success, greater benefit is achieved at the higher strength/hardness ranges above approximately 40 Rockwell 'C'. At this level, notch sensitivity of materials can cause problems and Fig. 5 shows how changing to materials with better ultimate properties can also result in better fatigue strength when shot peening is used as a final treatment. Case-carburised or through hardened parts in the 60-65 Rockwell 'C' range are ideal applications for shot peening.

DESIGN BENEFITS

To most designers shot peening is a tool to use in cases where problems have occurred on an existing piece of equipment. However, greater knowledge of the process and above all confidence in the reliability and repeatability of its application has meant its consideration at the design stage on new products. It is a design tool that can;-

a) prolong component life with fatigue strength improvement of 30%.
b) enable 20-40% high stress levels for the same life.
c) avoid redesign of gears by use of b).
d) allow reduced component size and weight for same fatigue strength.
e) enable use of higher strength steels without fears of notch sensitivity.
f) reduce the need for fine machining in fatigue critical components.
g) reduce costs by using less expensive materials.
h) enable the use of processes generally thought to reduce fatigue strength, i.e. E.C.M./E.D.M.
i) allow the use of hard facings on fatigue critical components.

These benefits can be achieved at minimal cost with high performance aerospace components, raising manufacturing costs by less than 1%. Automotive or general industrial parts, such as springs would increase costs from 1 - 10%, depending on size and complexity.

The type of component to benefit from the process is any part, ferrous or non-ferrous, suffering fatigue, fretting, stress corrosion cracking, galling or pitting. Certainly the most commonly known are springs, whether compression, tension, torsion or leaf and circlip shapes, belville washers, etc. Following closely behind are gears of all sizes, ranging from small reduction units on robotics applications to marine gears, metres in diameter. Here the bending fatigue strength can be increased by 20-40% giving life improvements on case-carburised gears of 8 - 12 times.

Shafts and axles or similar components, suffering rotational bending fatigue in keyways, splines, fillets, shear sections or any changes in cross section, can be treated with considerable improvement.

Hard chrome plated or hard anodised parts, subject to high stress, suffer from fatigue.This is due to the fine cracks which initiate in the plating or anodising (added to give a hard, wear resistant, protective surface) propagating through the coating into the softer base metal, Fig. 6.

If the surface of the base metal is residually stressed prior to the plating/anodising, the cracks will still initiate, but they will not propagate into the base metal.

An example is shown in Fig. No. 7 on high alloy steel rotational bending parts. This obviously applies to parts in manufacture and overhaul where they are re-machined or reground and then built up with a layer of chrome plate prior to re-installation. Plating alone without peening reduces fatigue strength by over 40% and peening regains almost the full fatigue strength.

Welded assemblies suffer fatigue and stress corrosion cracking because of high tensile stresses at the heat affected zone and surface impurities. Fig. 8 shows the improvements that can be expected in the as welded state or ground. Shot peening is replacing stress relieving by heat or vibration because it does more than just eliminate the tensile stress, it leaves the surface with a very high compressive stress not possible by the other methods. Weldments on pressurised vessels containing corrosive material or simply welded structural parts have been treated successfully.

Castings/forgings of all materials have been treated, including cast irons and aluminum to extend fatigue life. Porosity of aluminum valve bodies can be overcome and lubricity aided on seals by the generation of microscopic oil reservoirs on shafts.

CONTROLLED SHOT PEENING

The potential can only be achieved by controlled application of the process. This control producing a compressively stressed surface in which the level of stress and its uniformity,and the depth of the compressed layer, can be held constant from piece to piece. Lack of the correct control may not only prevent any benefits but may even cause premature failure. In this respect shot peening is no different to any other manufacturing process in that the quality of the treatment is directly proportional to the quality of the controls of application.

To date there is no practical non-destructive method for measuring the stress distribution in a finished part. Therefore, full control of the cold working of the surface is imperative. The desired stress, depth and magnitude, are obtained by the use of the right combination of shot, exposure time, shot velocity, feed rate, distance of part from source of shot, and angle of impingement. It is also imperative that the relative motion between the shot stream and the component be mechanised for uniformity and reproduceability.

Often the parameter singled out as being the most important is the peening intensity. Certainly it is important, but three other factors bear equal concern - these are Mechanisation, Media Quality and Coverage. Dyescan tracers can play an important part in three of these.

DYESCAN TRACERS - These are ultra-violet visible compounds that are brushed, sprayed or dipped onto a part and allowed to dry, forming a thin brittle film. Shot peening breaks up that film, leaving only the material that has not received direct impact. As the tracer is a fluorescent material, that area not receiving direct impact is clearly visible under a U.V. light. Therefore, the object of the process is to provide a practical way of measuring coverage in terms of the amount and uniformity of Dyescan tracer removal. Fully peened areas appear as a deep purple colour under U.V. light, whilst partially peened areas appear white or speckled white; results of a typical application - the peening of springs - are shown in Fig. No. 9. Here five springs were coated and the outer four peened to complete coverage. The photograph was taken under U.V. conditions, demonstrating the contrast obtainable. How that contrast is used to benefit when compared to the standard method of coverage determination - the 10 power magnifying glass - is explained below when the four critical aspects of shot peening are examined.

PEENING INTENSITY - J.O. Almen of General Motors Research Laboratories Division developed a method of measuring, specifying and duplicating shot peening intensities. The intensity being an indication of the kinetic energy transfer of the peening action which works on the principle that if a flat piece of metal is clamped to a solid block, and exposed to a blast of shot, it will be curved upon removal from the block. The curvature will be convex on the peened side. The height of the curved arc, measured on a special gauge, namely an Almen gauge, serves as a measure of intensity. The standards provide for three thicknesses of test strips suitable for different intensity ranges (Fig. No. 10).

If the reading of the 'A' strip is less than 0.004 in, the 'N' strip should be used; the 'N' strip readings will be about three times as high as those on the 'A' strip. If the reading on the 'A' strip is greater than 0.020 in., the 'C' strip should be used. It will give readings about 0.3 times those of the 'A' strip.

The standard designation on intensity measurement includes the gauge reading, or arc height, and the kind of strip used. It is necessary to specify a range, such as 0.010 in. to 0.014 in. A or 0.006 in. to 0.008 in. C. All measurements are made on the standard Almen No. 2 gauge as shown in the Military Specification MIL-S-13165B Amendment 2. (1)*

The test strip mounted on a holding block should be supported on a fixture which simulates, in its exposure to the blast, the critical surface of the part to be peened. For a more complicated part, a number of test strips may be needed on the same fixture. A test strip must not be re-used after peening.

When a series of test strips is peened with a fixed machine setting for different exposure times, a saturation curve, as shown in Fig. No. 11 can be obtained. The time necessary to produce saturation on the test strip can be defined as the time required to achieve the specified arc height at which doubling the exposure time will not increase the arc height by more than 10%. An arc height is not properly termed intensity unless saturation has been achieved.

It should be understood that the time required to saturate the test strip is not necessarily equal to the time required to saturate the part. If the hardness of the part is apprecably different from the 44 to 50 Rockwell 'C' hardness of the test strip, the time required to saturate the part will, of course, vary. For instance, a carburized part will take longer to saturate and a soft material will reach a point of saturation faster. The hardness of shot can also influence required time.

Dyescan tracers are a useful tool during this pre-production stage of establishing the correct peening intensity uniformly over the component. As stated earlier, on complicated parts such as a larger aero-engine fan blade, it would be necessary to locate on a dummy component Almen blocks at the leading and trailing edges; around the snubber and at angles simulating the fretting pressure faces of the dovetail. Coating that blade with Dyescan at the same time as fitting Almen strips to check correct intensity in the critical areas will indicate, if the process is checked at frequent intervals, the rate of work done, highlighting areas being shielded, overpeened or indeed a machine malfunction. Thus enabling a speedy redistribution of nozzles to uniformly cold work the surface and achieve the intensity required.

COVERAGE - is defined as uniform denting or obliteration of the original surface of the part or work-piece. Shot peening, unless it is for forming or straightening, would necessitate complete coverage and this, generally, is accepted

*Numbers in parentheses designate references at end of paper.

as approximately 100%. Most aerospace standards call for coverage in excess of that rate, or in multiples of it, as a good production standard and safety factor. This safety factor has been employed because a single indentation has a hoop tensile stress in the area surrounding it. Although the cold worked area is approximately four times the indentation area, the outer annulus sees the maximum compressive stress diminishing to zero and then proceeding to low-magnitude tension; hence the need to have overlapping indentations to achieve the maximum potential.

Tests conducted by Person (2)* of the Kaiser Aluminium & Chemical Corporation on some aluminum forgings have highlighted the critical nature of coverage. The report investigated the different parameters of peening and indicated how they affected the fatigue life of these forgings. Whilst the results should only be read as applying to these particular components, they do show that once a set of parameters has been established there should not be departure from them unless fatigue tests have been conducted to justify the change. The coverage tests indicated that with under-peening to only 80% coverage, the fatigue life was only 38% of that achieved at approximately 100% coverage.

The method employed for many years for checking coverage, because no alternative was available, was the use of the 10-power magnifying glass. Whilst this is indeed a good tool - because not only can the coverage be checked but the media quality can also be inspected -factors of accessibility and personal fatigue must be considered.

Large components, or large productivity batches of small components, would also cause problems. In addition, deep holes or grooves and complicated geometrical shapes do not always allow visual inspection, although the majority of areas are no problem, particularly on flat sections or plain diameters. However, as the shot peening process is carried out to eliminate or considerably reduce crack initiation and subsequent propagation, and as it is more than likely that any failure that does occur will initiate from a hole, groove or complex shape rather than from an easily visually inspected plain area, the inspection approach should favor the method most likely to indicate under-coverage or under-peening in the most critical areas.

Dyescan is not being suggested as a replacement of the 10-power glass, but an addition to the quality control armour.

Below 55 Rockwell 'C' visual inspection with the glass improves with the reduction in hardness. Fig. No. 12 shows the effect on 40 Rockwell 'C' steel in the complete and partial state indicating the ease of detection on softer surfaces. However, above that figure - especially with parts in the 60 Rc range - visual inspection, even for the most experienced becomes very difficult.

All personnel involved with the shot peening process have at some time or other been involved in discussions as to whether an area has or has not been peened, to the point that the inspection becomes a subjective argument. Dyescan tracers turn that argument into a more objective definition by turning the peened/unpeened areas into a black/white situation.

Low angle of impingement will not remove all tracer coatings, and uneven peening and hot-spot concentration can be seen by patterns of remaining coatings.

Owing to the gradual breakup of the brittle film, this principle is used in setting up and establishing peening techniques, such as nozzle angle, distance, number and feed rate. Prior to reaching optimum coverage of a component, it has to be established that peening is being achieved uniformly or at least that the areas most critical on a component are being concentrated on most. To achieve this during the initial setting stages, a component will be removed from the peening enclosure several times until the pre-determined coverage rate is met: this is illustrated by Fig. 13 which relates to the progressive peening of a turbine blade root.

Fig. 13a is an unpeened coated blade root photographed in natural light; 13b photographed in U.V. light; 13c to f progressive peening at 15 seconds intervals demonstrating the gradual removal. It will be seen that the pocket under the platform is the last to clear, verifying the comments made previously on holes, grooves, etc. Note that the bottom of the root is taped with Dyescan imbedded which will remain as the surface is ductile.

Surface finish problems arising from coarse machining or even welding are highlighted by the Dyescan remaining in the roots or valleys. This could indicate a change in the surface texture not detected by the quality control department; the welds would need dressing prior to peening or the shot size would have to be reduced to reach the valleys. Similarly, where the Dyescan has been used on the first samples for coverage determination during initial setting procedures, a subsequent incorrectly machined part with sharp corners will stand out vividly under U.V. conditions where the shot has not penetrated the corner. An example is given in Fig. No. 14 of the shaft peened in the threaded area for many years, but on this batch several parts had a poor thread form. This resulted in the Dyescan not being removed from the roots and was vividly demonstrated at the U/V inspection stage.

Owing to the rapid use of shot peening on chemical, food and brewery plants to cure stress corrosion problems, Dyescan cuts processing costs by drastically reducing inspection time. Some of these vessels may be 5, 10 or 20 metres in diameter, which inspecting by any other method would be impractical. An example of what peen-

*Numbers in parenthese designate references at end of paper.

ing can do for stress corrosion cracking prevention is shown in Fig. 15.

MECHANISATION - Mechanisation of the process has been well demonstrated as essential for consistency and the Military Specification 13165B on Shot Peening of Metal Parts (1) - the forerunner of most aerospace peening specifications-confirms this by firmly stressing that it is the only approved method. Whilst manual processing is carried out, it can only be applied where reliability is not necessary or Dyescan Tracers are used, not as a percentage check, i.e. one in ten or twenty, but 100%. Manual work, unless accompanied by Dyescan must never be applied to aerospace components where the compressive stress generated by the shot peening may be part of the initial design criteria.

All equipment used must have a mean of propelling shot by air pressure or centrifugal force against the work, and of mechanical means of moving the work through the shot stream by linear motion or rotation, or both, as required. Essentially, the equipment must be capable of reproducing the shot peening parameters established during initial trials and in the proving of results.

Without mechanisation, uniformity of coverage and hence uniformity and consistency of depth and magnitude of compression, cannot be guaranteed.

MEDIA QUALITY - This is an aspect that is often ignored, but one so necessary in maintaining the maximum potential of the process. It is the shape and size of the particle that generates the shape and size of the indentation and insufficient working of the surface, along with cutting or abrading of the surface, considerably reduces the peening effect. It is imperative that only good media is used and that specified in the Military Specification 13165B (1) affords an excellent start. However, its use without grading continually in terms of size and shape will cause a deterioration in the quality of the shot peening in parallel with the reduction in the quality of the shot. The media must be constantly monitored and graded to ensure repeatability.

CONCLUSIONS

There has been a need for Dyescan tracers for many years, and the data before identifies the reasons why they have been taken up so readily by industry. They are not intended to eliminate 10-power glass, but compliment it by tackling areas not easily accessible or not practical, such as large surfaces or very hard steels. Consequently, several major companies, including Aerospace, Commercial Vehicle, Marine, Turbine and Gear Manufacturers - use the method to improve their shot peening standards and therefore reliability.

REFERENCES:

(1) - Military Specification on Shot Peening of Metal Parts, MIL-S-13165B, Amendment 2, 25th June, 1979.

(2) - Neal L. Person, Effect of Shot Peening Variables on Fatigue of Aluminum Forgings, Metal Progress (July 1981) 33-35.

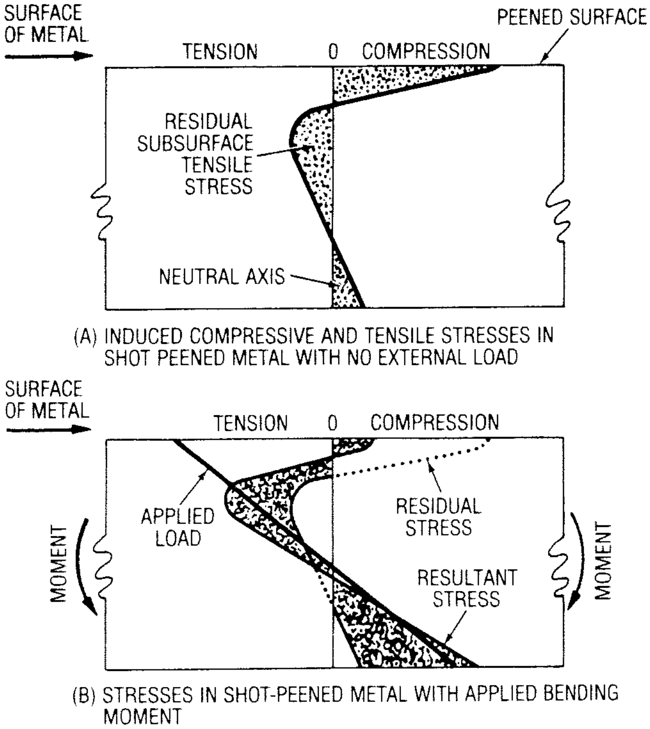


FIG. NO. 1 COMPRESSIVE STRESS INDUCED IN THE SURFACE OF A SHOT-PEENED BEAM (A) PREVENTS SURFACE TENSILE STRESSES FROM OCCURRING AFTER A BENDING MOMENT IS APPLIED (B).

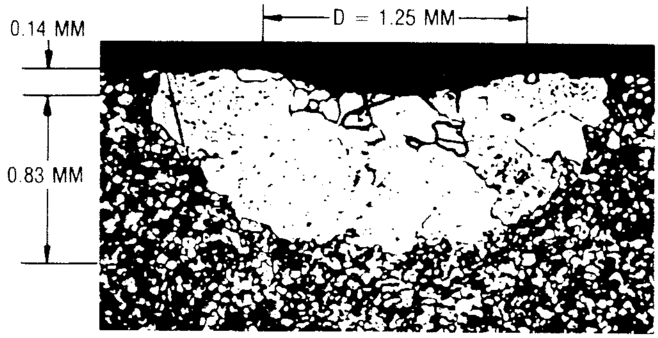


FIG. NO. 2 PHOTOMICROPGRAPH SHOWING A SINGLE DIMPLE INDENTATION THAT RESULTS FROM A 6.4MM STEEL BALL AT A HIGH PEENING INTENSITY.

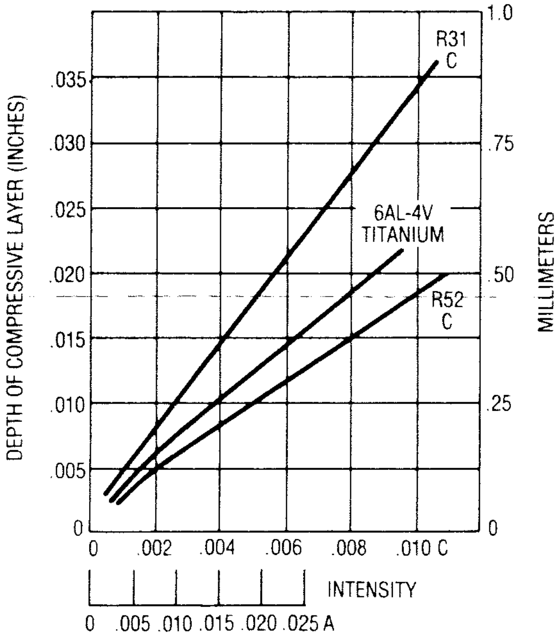


FIG. NO. 3 DEPTH OF COMPRESSIVE STRESS VS. ALMEN INTENSITY FOR STEEL & TITANIUM.

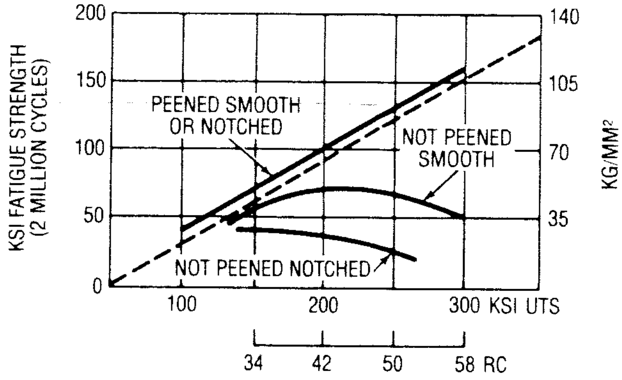


FIG. NO. 5 COMPARISON OF PEENED AND UNPEENED FATIGUE LIMITS FOR SMOOTH AND NOTCHED SPECIMENS AS A FUNCTION OF ULTIMATE TENSILE STRENGTH OF STEEL.

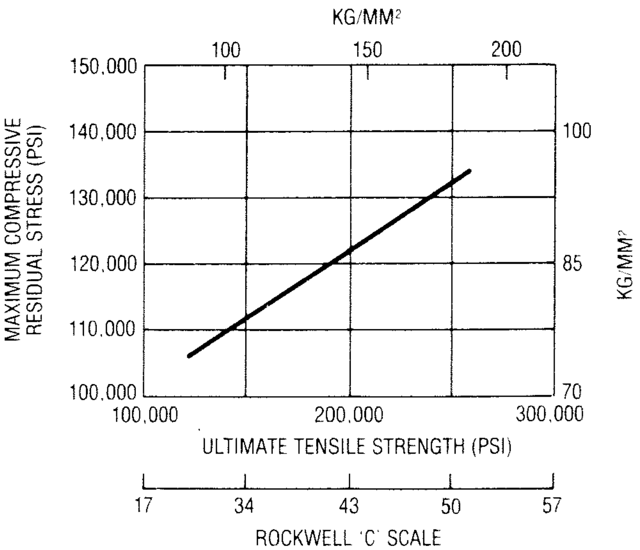


FIG. NO. 4 RESIDUAL STRESS PRODUCED BY SHOT PEENING VS. TENSILE STRENGTH OF STEEL.

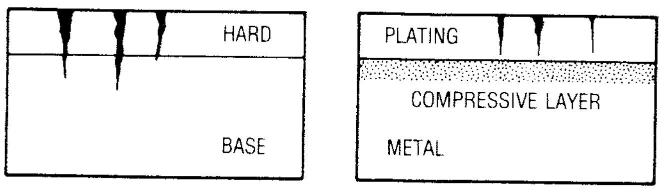


FIG. NO. 6 PLATING CRACKS WILL NOT PROPAGATE INTO PRE-STRESSED BASE.

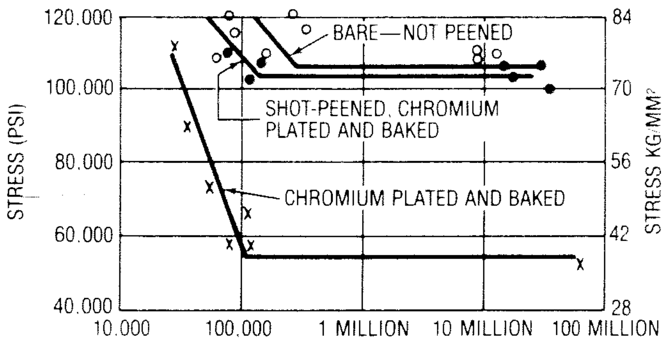


FIG. NO. 7 CYCLES TO FAILURE
4340 STEEL, 52-53R_c ROTATING BEAM FATIGUE.

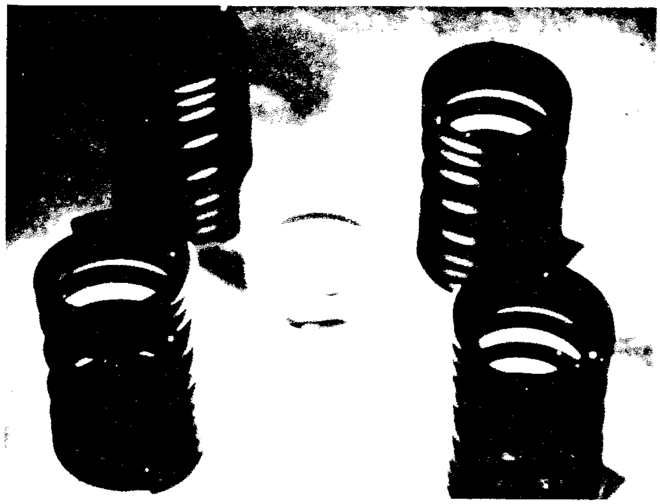


FIG. NO. 9 FIVE SPRINGS COATED WITH DYESCAN AND FOUR PEENED TO SHOW THE CONTRAST UNDER U.V. CONDITIONS.

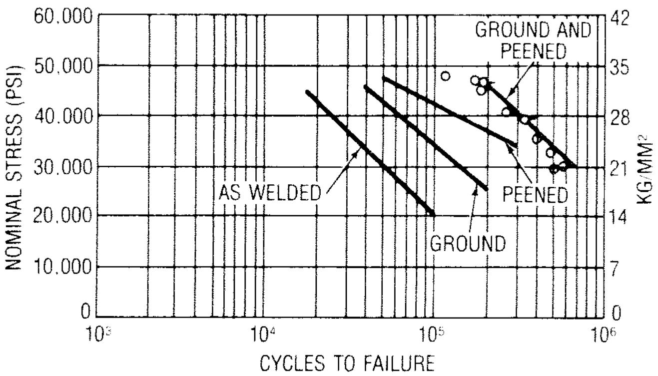
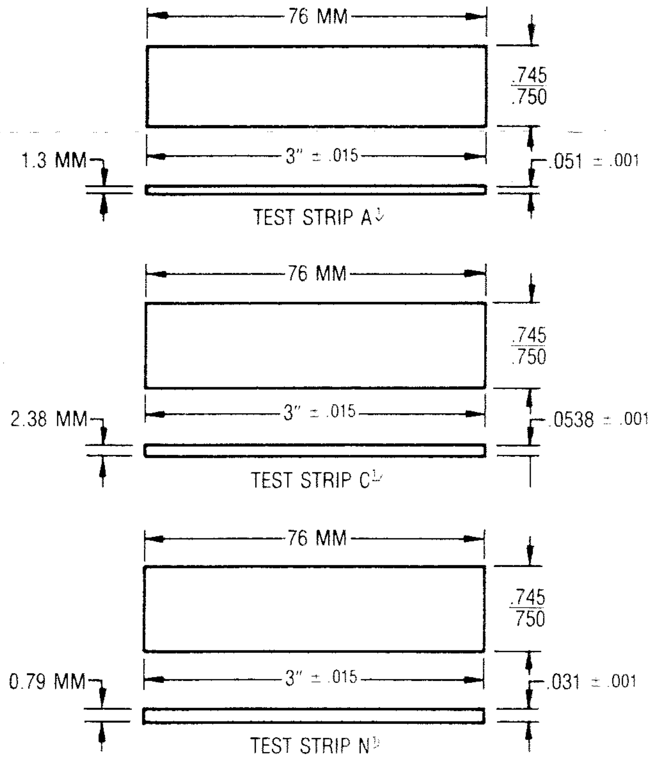


FIG. NO. 8 S/N CURVES FOR WELDED BEAM TYPE SPECIMENS COMPLETELY REVERSED STRESSES.



TEST STRIP SPECIFICATIONS

ANALYSIS OF STOCK—SAE 1070
COLD ROLLED SPRING STEEL
SQUARE EDGE NUMBER ONE (ON 3" EDGE)
FINISH—BLUE TEMPER (OR BRIGHT)
UNIFORMILY HARDENED AND TEMPERED TO 44-50 RC
FLATNESS— ± .0015" ARC HEIGHT AS MEASURED ON ALMEN GAUGE.

FIG. NO. 10

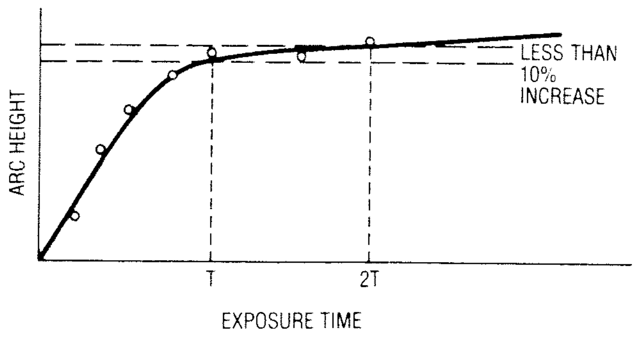
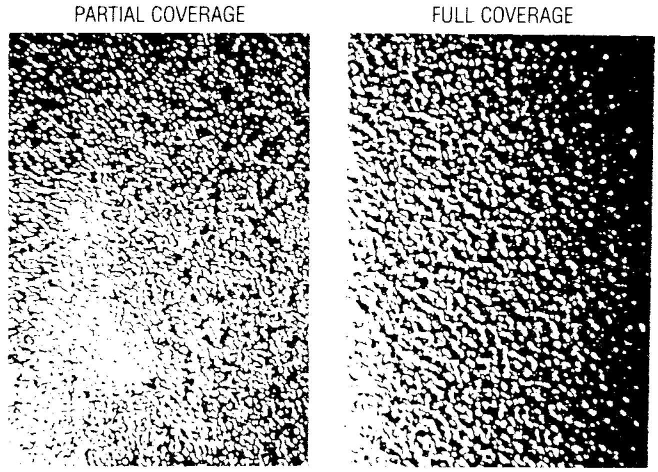


FIG. NO. 11 SATURATION CURVE



PART OF ORIGINAL SURFACE VISIBLE BETWEEN DIMPLES. DIMPLES NOT OVERLAPPING.

COMPLETE DIMPLING OF ORIGINAL SURFACE. ORIGINAL SURFACE COMPLETELY OBLITERATED BY OVERLAPPING DIMPLES.

FIG. NO. 12

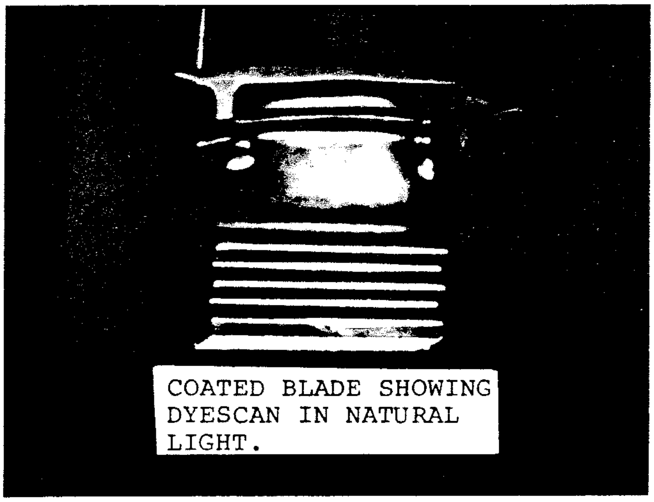


FIG. 13a

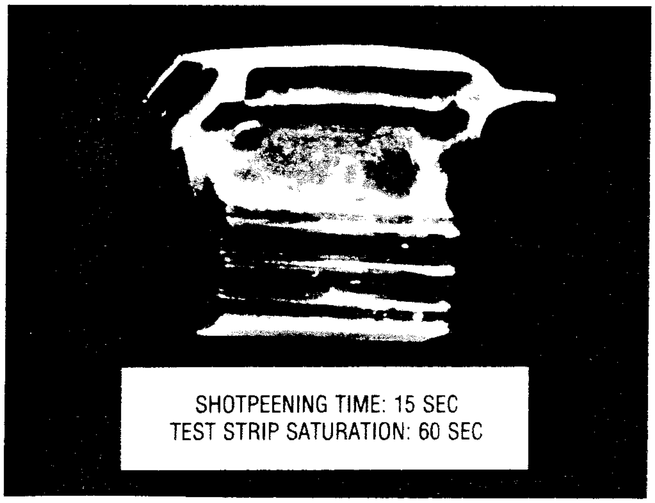


FIG. 13b

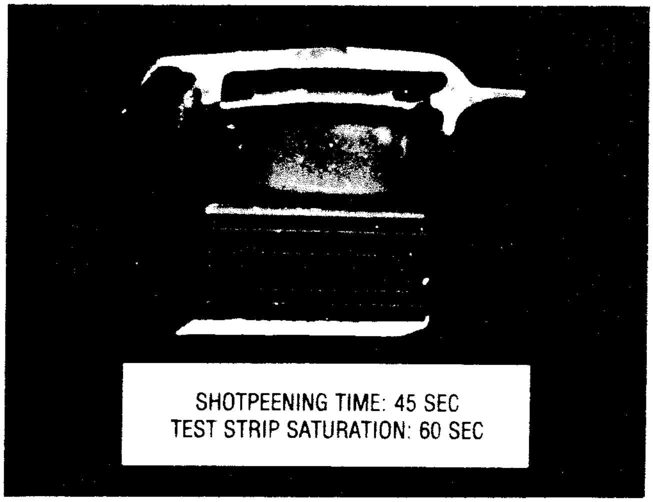


FIG. 13c

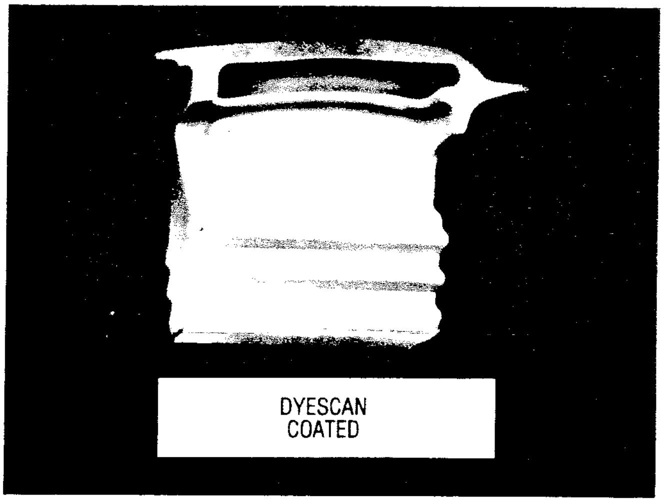


FIG. 13d

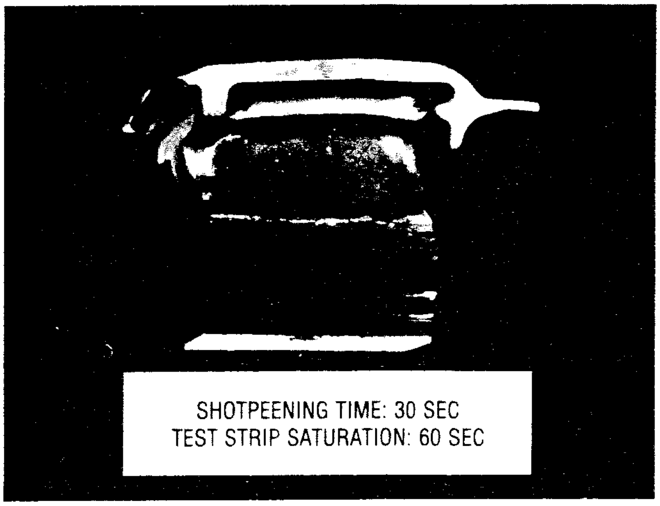


FIG. 13e

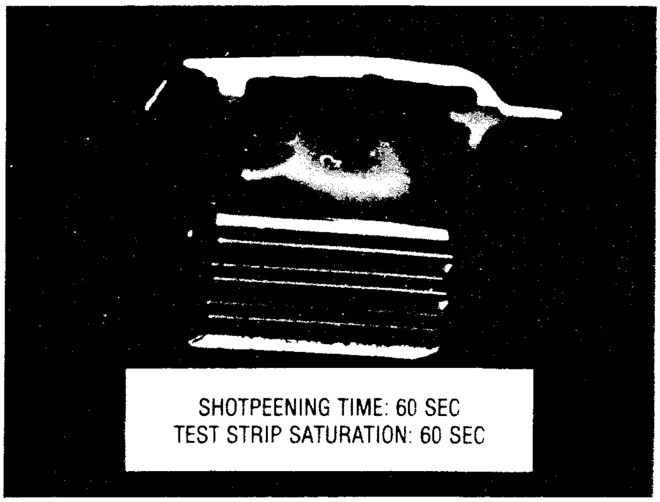


FIG. 13f

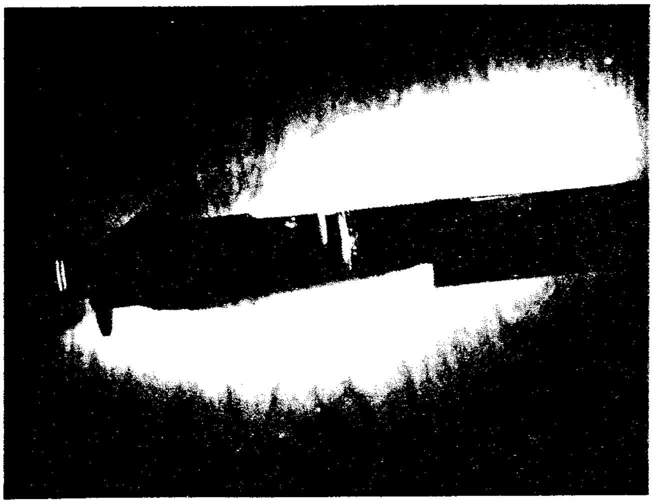


FIG. NO. 14

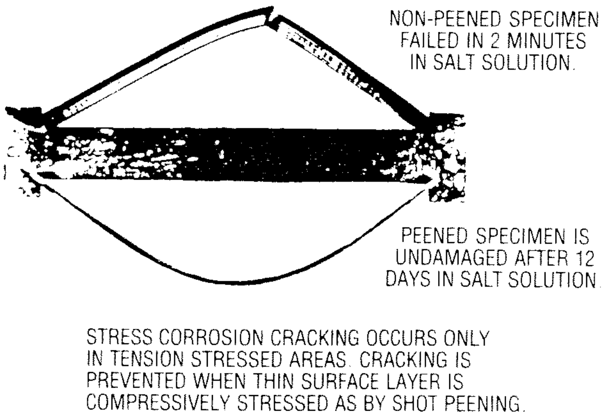


FIG. NO. 15 STRESS CORROSION IN MAGNESIUM