THE USE OF SHOT-PEENING AS A MEANS OF REDUCING FATIGUE FAILURES IN METAL COMPONENTS

by

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INTRODUCTION:

Shot-peening is the term used to describe the process of hammering the surface of metal machine and structural parts with relatively high velocity stream of steel or chilled iron particles. This treatment cold-works and pre-stresses the surface of the component and as a result its resistance to failure by fatigue may, under favourable conditions, be considerably improved. The process has been applied to a variety of parts and in many cases quite spectacular increases in fatigue life have been recorded. For example, Almen[1] gave the results of peening some typical machine components such as shafts, gears and springs which showed increases in life after peening of 400 to 1400 per cent.

EFFECTS OF SHOT-PEENING ON MATERIAL:

As each shot particle strikes the surface it makes a small indentation in the vicinity of which the material is cold-worked. The cold-worked layer near the surface may be seen in Fig. 1(a) which shows the effect of peening a mild steel. Fig. 1(b) shows a similar part with a ground surface for comparison. The depth of the work-hardened layer so formed has been estimated to be of the order of 0.005 inch.

This work-hardening increases the strength of the surface layer by a significant amount, Brookman and Kiddle[2] showed that the Vickers[2] Diamond Pyramid hardness of a particular steel specimen was increased from 350 in the initial material to a value in excess of 400 near the surface after peening. This corresponds to an increase in the nominal tensile strength of the surface material in this instance from 75 to something over 85 ton per sq. in. As fatigue failures commonly originate at the surface it is evident that this increase in the strength of the surface material should result in an improvement in fatigue life.

In addition to increasing the strength of the surface material by work-hardening, peening also induces residual compressive stresses in the surface layer. The residual stress pattern in a peened part may be represented diagrammatically as shown in Fig. 2. In this diagram the depth scale has deliberately been distorted, being magnified near the surface and reduced in the centre. The peak residual compressive stresses can be very high—of the same order of magnitude as the stresses induced by the external applied load.

The effect of this residual stress may be visualized by considering a component subjceted to an external applied bending moment. The stress distribution in the loaded component may be represented by the dotted line in Fig. 3, where C_1 represents the maximum compressive stress and T_1 the maximum tensile stress. If now the residual stresses are added algebrically to the applied stresses, the resultant stress pattern will be as sown by the full line in Fig. 3. It is clearly seen that the maximum tensile stress has been reduced while the maximum compressive stress has been increased. It is argued that fatigue failures start in the region of maximum tensile stress, and the reduction in tensile stress by the residual compressive stress arising out of the peening treatment is one of the main reasons for the improvement in fatigue life.

Another effect of bombardment with shot is to roughen the surface. Compare Figs. 4(a) and (b). This point is further illustrated in the surface roughness charts Fig. 5.

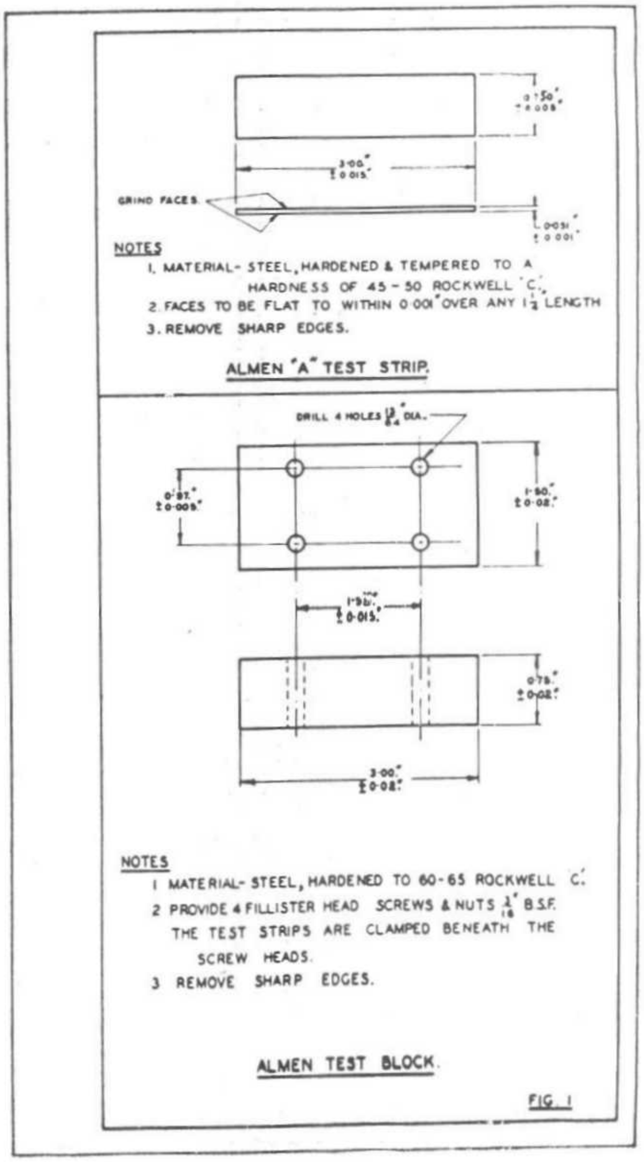
3·00"
± 0·015"
GRIND FACES
NOTES
1. MATERIAL- STEEL, HARDENED & TEMPERED TO A HARDNESS OF 45 - 50 ROCKWELL "C".
2. FACES TO BE FLAT TO WITHIN 0·001" OVER ANY 1½" LENGTH
3. REMOVE SHARP EDGES.
ALMEN "A" TEST STRIP.
DRILL 4 HOLES 13/64" DIA.
1·50"
± 0·02"
± 0·015"
0·75"
± 0·02"
3·00"
± 0·02"
NOTES
1 MATERIAL- STEEL, HARDENED TO 60-65 ROCKWELL "C".
2 PROVIDE 4 FILLISTER HEAD SCREWS & NUTS 3/16" B.S.F. THE TEST STRIPS ARE CLAMPED BENEATH THE SCREW HEADS.
3 REMOVE SHARP EDGES.
ALMEN TEST BLOCK.
FIG. 1

Fig. 1

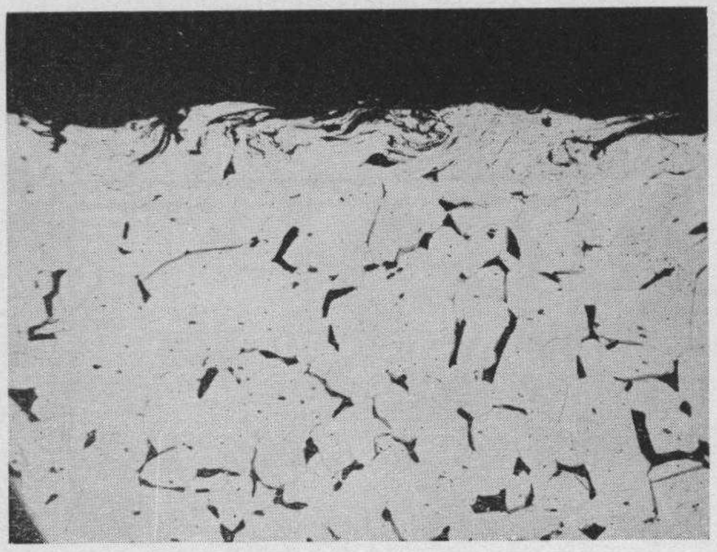

Fig. 1 (a)
Mild steel specimen shot peened surface

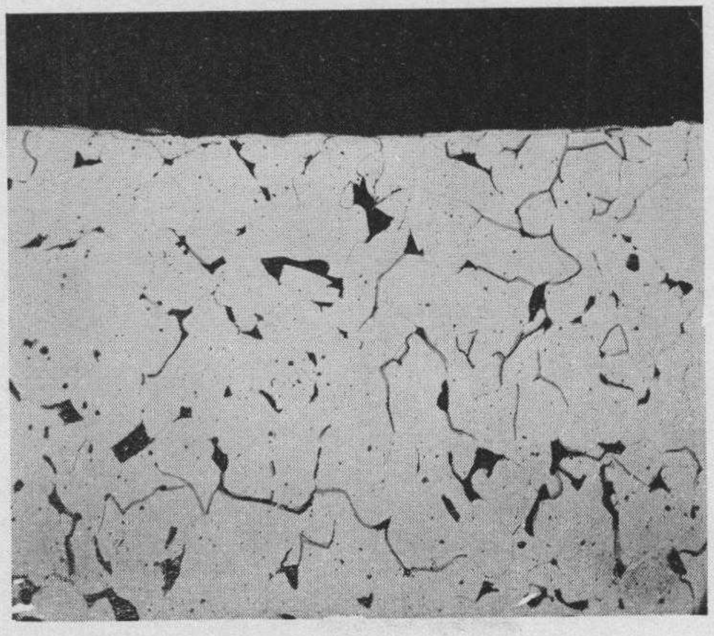

Fig. 1 (b)
Mild steel specimen ground surface

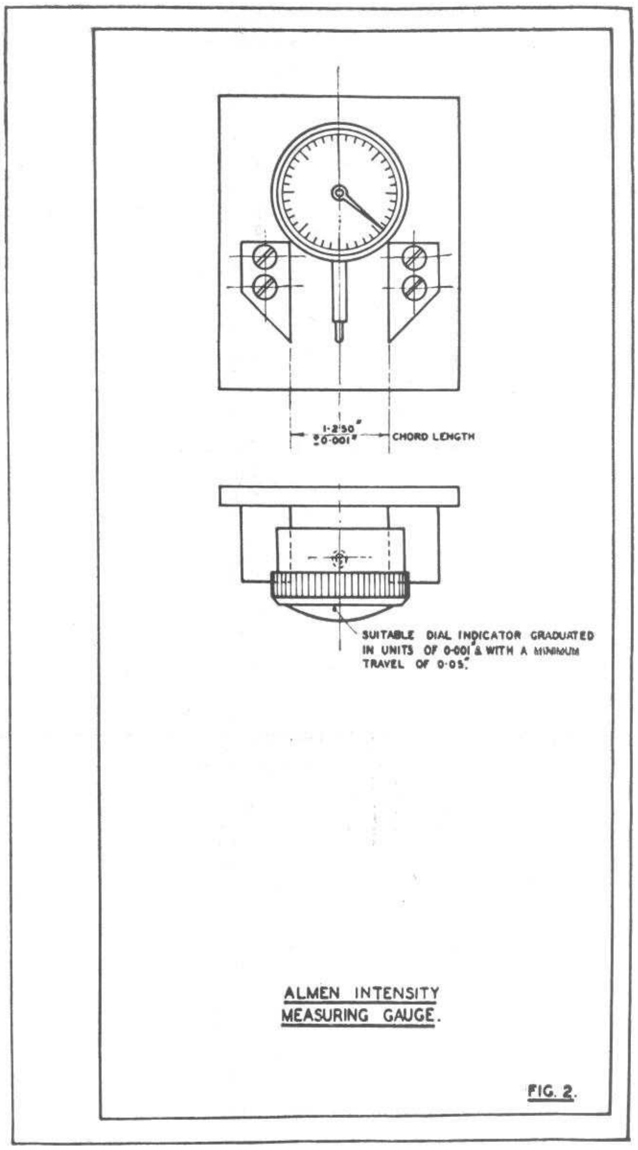
1·250" ±0·001"
CHORD LENGTH
SUITABLE DIAL INDICATOR GRADUATED IN UNITS OF 0·001" & WITH A MINIMUM TRAVEL OF 0·05".
ALMEN INTENSITY MEASURING GAUGE.
FIG. 2.

Fig. 2

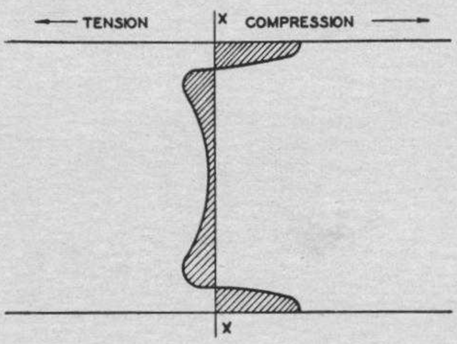

FIG. 2.

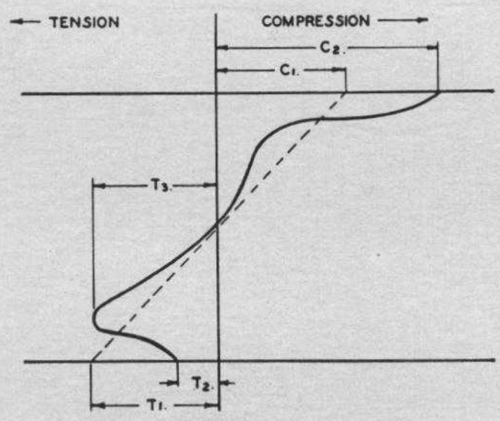

FIG. 3.

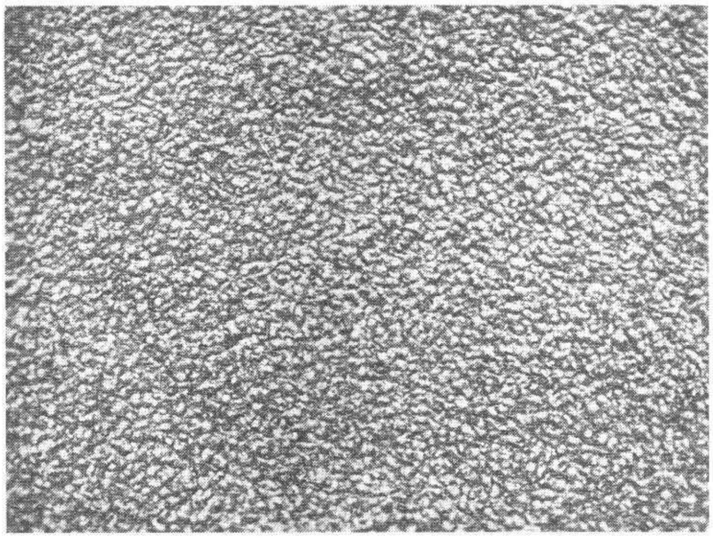

Fig. 4 (a)
Mill steel specimen. Shot peened surface. Surface roughness.
R.M.S. 130-170 Micro-inch

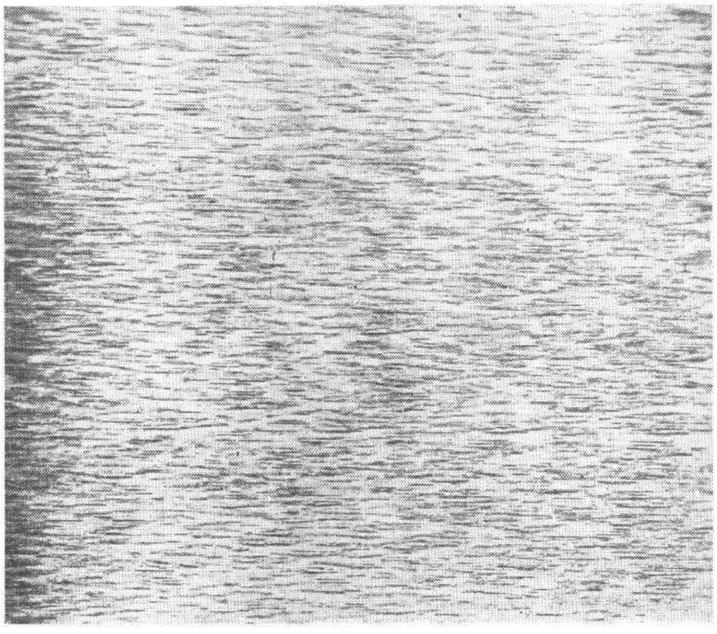

Fig. 4 (b)
Mild steel specimen. Ground surface. Surface roughness.
R.M.S. 20 Micro-inch

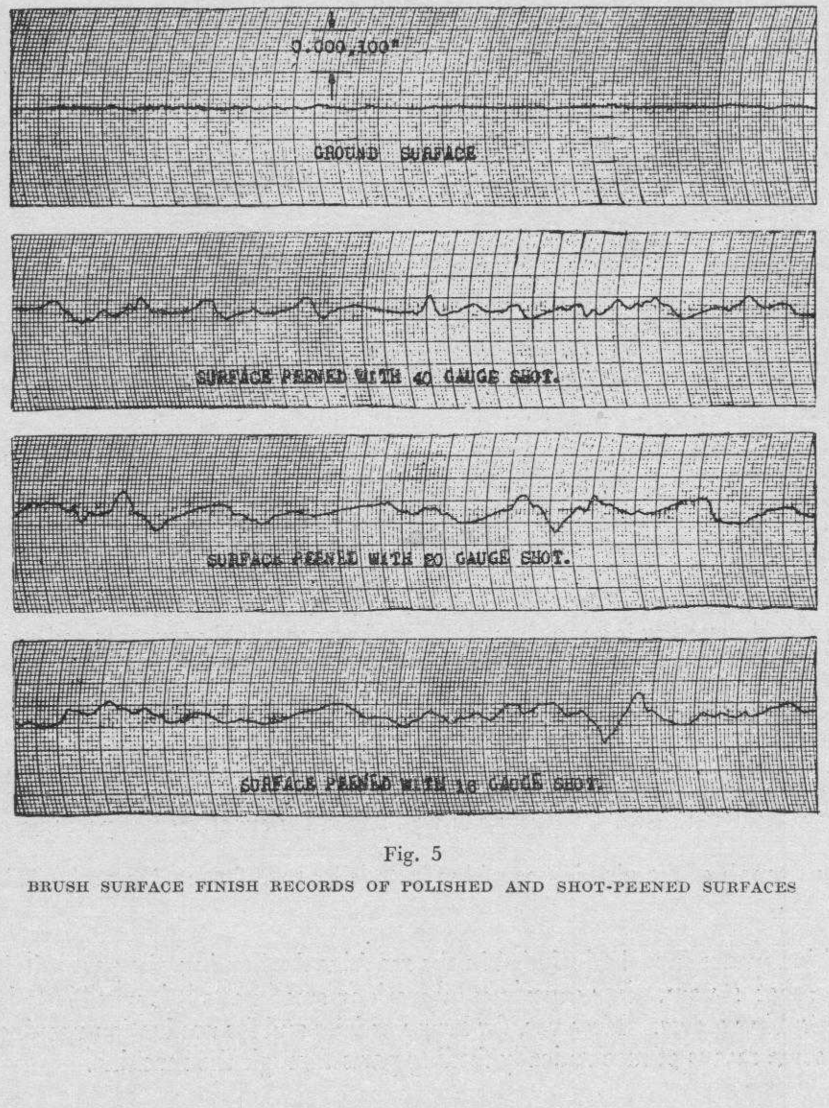

Fig. 5

BRUSH SURFACE FINISH RECORDS OF POLISHED AND SHOT-PEENED SURFACES

Although, it is well established that a rough surface has a detrimental effect on fatigue life, (e.g. a coarsely turned surface would give a lower fatigue limit than a fine turned or ground surface in the same material) the surface roughening effect of peening does not seem to be quite as bad as would at first appear. Each indentation in the surface of the peened material may be considered as a small stress concentrator or notch, and the bad effect of small stress raisers is the main reason for the reduction in fatigue life mentioned above. However, the effect of a single-notch is very much reduced by the presence of similar nothces close by. It seems that many nothches close together share the stress concentration between them whereas an isolated notch has no such relief from the full stress concentration. Another point is that the notches introduced by peening would have a well-rounded bottom because the indentation is made by spherical or, at least, well-rounded particles and the stress concentration of such a notch is much less than would be obtained, for instance, from a sharp continuous notch such as a tool mark on a turned surface.

Summing up then, it may be stated that the effects of shot-peening on the material are :—

1. Beneficial

(a) Cold-working which raises the strength of the surface.

(b) Introduction of residual compressive stress which reduces the peak tensile stress at the surface.

2. Deleterious

(a) Surface roughening which introduces stress-raisers or notches.

(b) Probable increase of notch sensitivigy of the surface because of the work-hardening. This would accentuate the effect of 2(a).

It may be stated that the beneficial effects of the first two factors, in many cases, more than outweigh the deleterious effects of the latter two factors so that the overall effect of peening is an improvement in the resistance to failure by fatigue.

EQUIPMENT AND APPLICATIONS:

1. Peening Machines

The peening machine consists essentially of some means of accelerating the shot to the required velocity and directing it on to the work piece in a reasonably concentrated stream. There are two main types of machine used for this purpose. In one type the shot is fed into the centre of a rapidly rotating bladed wheel and is thrown outwards by centrifugal force. This type of machine can deal with large quantities of shot (about 250 pounds per minute) but it is difficult to control the shot stream when peening localized areas. The other type of machine utilizes an air jet to bring the shot particles to the required velocity. This type handles a rather smaller quantity of shot (up to 100 pounds per minute) but it is easy to produce a concentrated shot stream and direct this over localized areas. This type is well suited for experimental peening.

A photograph of the air-blast machine installed at Defence Research Laboratories is shown in Fig. 6.

In addition means must be included in the machine for keeping the part suitably placed in relation to the shot stream. For experimental work on small parts it is possible to hold the part by hand with rubber gloves. However, for larger articles and for production peening it is necessary to have some means of mechanically feeding parts through the machine.

2. Masking

In many cases it is not necessary to peen the whole surface of parts and in certain cases it is essential that the peening be restricted to certain areas. In such cases it is necessary to protect areas which are not to be peened by suitable metal or rubber masks firmly attached to the selected areas.

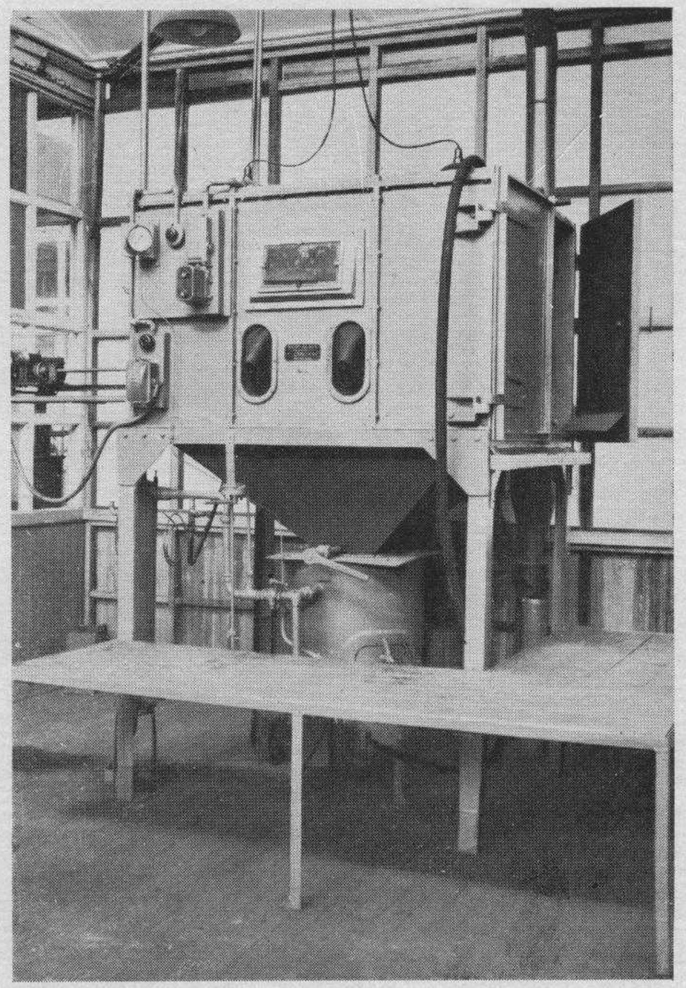

Fig. 6
Air Blast Shot-Peening Machine Installed at D.R.L. Maribyrnong

3. Control of the process

The process is controlled by close attention to (a) the velocity and particle size distribution of the shot stream, (b) peening time and (c) shot type and size. It will be convenient to consider each of these factors separately.

(a) Velocity and particle size distribution of the shot stream

Two convenient methods of control of this factor have been worked out by Almen[1] and Brookman and Kiddle [2]. In each case the method consists in peening one surface only of a heat-treated flat steel strip. The residual compressive stresses on the one side caused the strip to bend and the amount of bending is measured by means of a dial gauge. The method is purely arbitrary but has proved satisfactory in practice. The measured deflection of the test strip has been given the name "intensity".

The Almen test strips are 3″ long, 0.75″ wide and either .051″ or .094″ thick. They are held in a steel block by four screws during the peening operation. The strip after being peened, is held in place on the anvil of a small gauge and the deflection between two gauge points 1.25″ apart is measured.

The Brookman and Kiddle apparatus uses a strip 3″ long, 1″ wide and 0.085″ thick. This strip is clamped in a holder with a length of 2″ projecting and peened on one side. The strip is then clamped in a block and the deflection is measured at a distance of $1\frac{1}{2}$″ from the edge of the clamp. It is claimed for this method that the test strips are easier to prepare and give greater sensitivity.

In use the test block containing the strip is mounted in position on a dummy component and run through the machine in the usual way. The test strip is then removed from the block and the "intensity " measured. If this is within the specification limits, peening may proceed. If not, adjustments are made to the shot stream until the intensity is with in the desired limits.

Admittedly both of these methods give a measure of the combined effects of velocity and particles size, but they have been found to be satisfactory in practice. The measurement of the arbitrary quantity "intensity" has proved to be a very satisfactory method of control of the peening operation. A value of "intensity" of 0.013″ to 0.015″ as measured on the Almen "A" strip has been found to give generally satisfactory results.

(b) Peening Time

The peening time needs to be adjusted to obtain full coverage without wasted effort. Practice at D.R.L. is to examine the surface being treated under a low power binocular microscope and determine the time taken to just cover the complete surface, then peen the parts for an additional 25 to 75 % of this time. Experience has shown this practice to give satisfactory results. It is important to ensure that the surface be peened uniformly over the whole area being treated.

The effect of time of peening on intensity measuring strips of the Brookman and Kiddle type is shown in Fig. 7. The intensity in this case did not increase substantially for peening times in excess of 20 seconds. It is interesting to note that 20 seconds was the estimated time for full coverage.[2]

(c) Shot Type and size

The shot used for metal peening must consist of well-rounded particles with a minimum of chipped or broken pieces, which abrade and cut the surface rather than peen it. Chilled cast iron shot has been used at D.R.L. up to the present time. This shot has proved quite suitable for the purpose although it has a tendency to break up rather rapidly. The size which has been most used is known as 20 guage (average particle diameter 0.03″) but other sizes, both smaller and larger than this, have been used. An interesting paper on shot for metal peening has been contributed by O.E. Harder and J.T. Gow.[3]

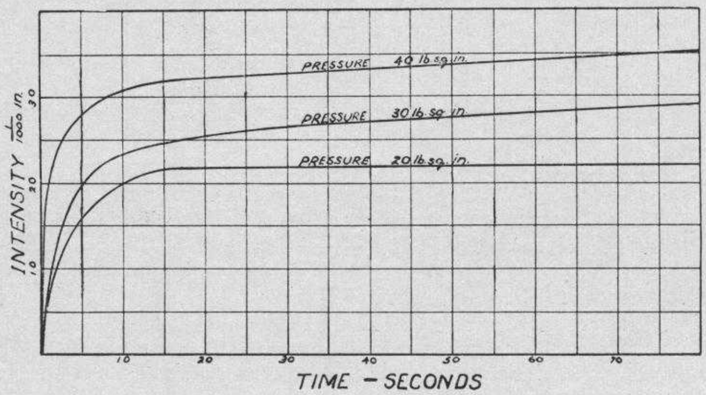

Fig. 7
Graph of Peening Intensity against time. Brookman & Kiddle Test Strip.

An extremely interesting pointer to the future is the use of cut-wire shot for peening.[4] This material offers advantages from the point of view of cost and improvements in fatigue life. This type of shot is not available in Australia as yet and consequently has not been tried at D.R.L.

SPECIFICATION:

For reference purposes a draft specification to govern the shot-peening of a typical aircraft structural component has been included in an Appendix. This specification is similar to one prepared by D.R.L. to cover the peening of an assortment of aircraft under-carriage components and is based on our current practice.

APPLICATIONS:

The following notes illustrate some typical applications of the shot-peening treatment. This list is not by any means exhaustive.

Coil springs are commonly shot-peened and are very suitable subjects for this treatment. It is necessary to make sure that the springs are peened all over, particularly on the inside of the coils. Small springs can be peened by rumbling them inside a drum and directing the shot stream into the drum. Coil springs have been shot-peened since the year 1929[5].

Leaf springs are often shot-peened, usually on the tension side only.

Connecting rods for aircraft engines are being shot-peened very extensively at the present time but there is little evidence in the literature on the results of the treatment of peened rods compared with un-peened rods. A description of the method used by the Studebaker Company is given in reference[6].

Gears of many types have shown remarkable improvements in fatigue life and methods for their shot-peening are well established.[7,8]

Axles from a variety of automotive vehicles have been shot-peened at D.R.L. with very satisfactory results.

Many other types of component particularly in the air-craft and automobile fields, have shown beneficial results after peening and it is safe to say that the range and variety of parts treated will increase in the future.

SOME TEST RESULTS:

It was mentioned in the introduction that in certain cases quite remarkable increases in the number of cycles to failure have been recorded. However, these results have been mostly obtained from tests on components in service. The author believes that such tests are unsuitable for determining the basic characteristics of the effects of shot-peening, mainly because of the difficulty in controlling the many variables present. For example, the stresses are seldom, if ever, known with any degree of precision ; the stress concentration conditions are generally difficult to control and evaluate ; the loading often varies considerably with time, and so on.

To enable a balanced picture of the effects of shot-peening to be obtained, research work is proceeding at the Defence Research Laboratories with a view to separating, to some extent, the effects of the many variable factors present. Some tests have been carried out on a 0.6% Carbon steel, heat-treated to an ultimate tensile strength of 60 ton per sq. in. The tests were run on high speed rotating bending fatigue testing machines running at 12,000 r.p.m. Two important variables have been considered, namely, (1) the method of surface preparation and (2) stress concentration. The mean results of tests on turned and ground specimens of both plain and notched forms are given in the S-N curves. (Figs. 8 to 11).

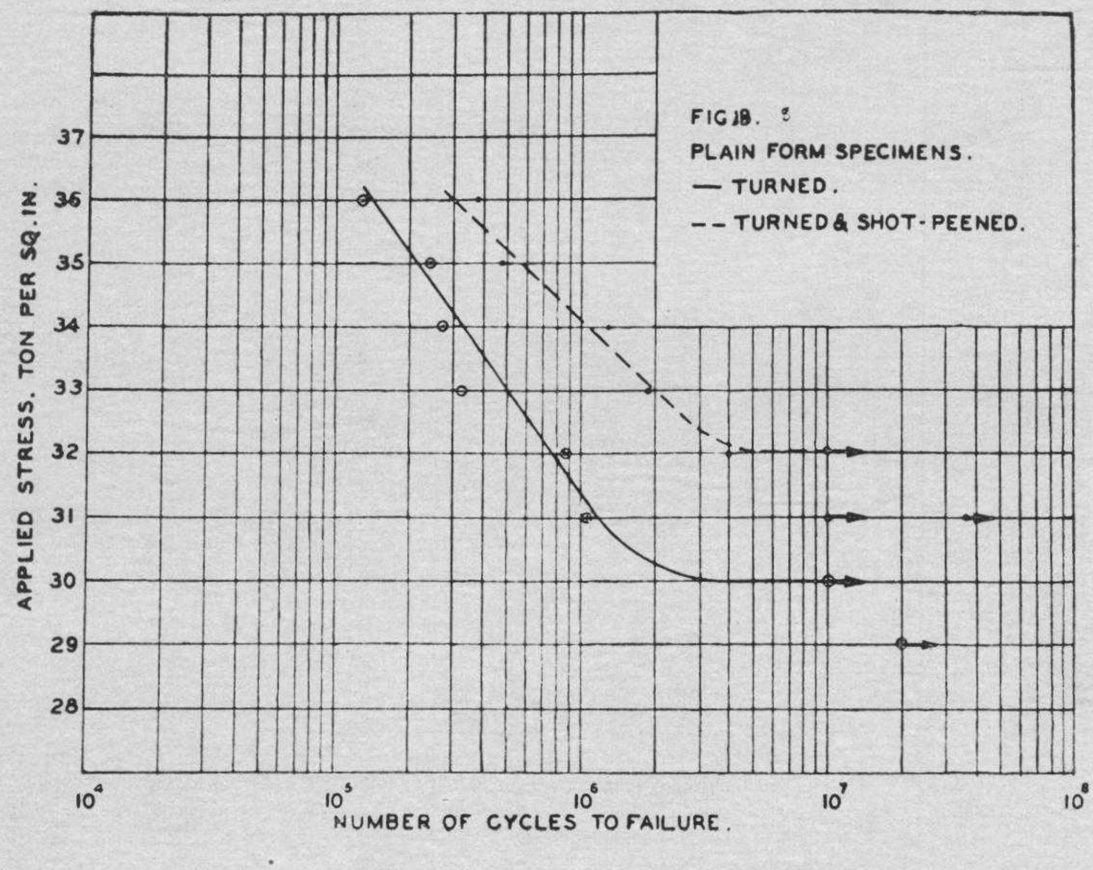
FIG 18. 5
PLAIN FORM SPECIMENS.
— TURNED.
-- TURNED & SHOT-PEENED.
APPLIED STRESS, TON PER SQ. IN.
37
36
35
34
33
32
31
30
29
28
10^4
10^5
10^6
10^7
10^8
NUMBER OF CYCLES TO FAILURE.

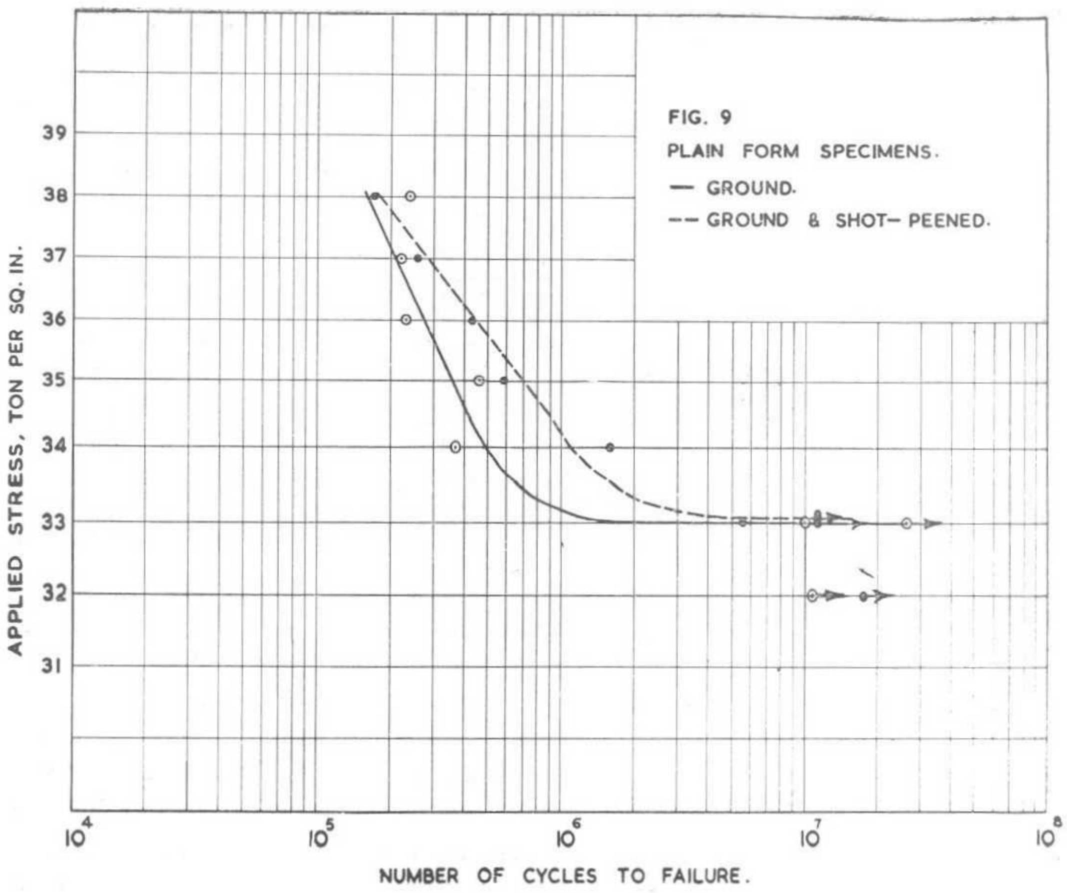

FIG. 9
PLAIN FORM SPECIMENS.

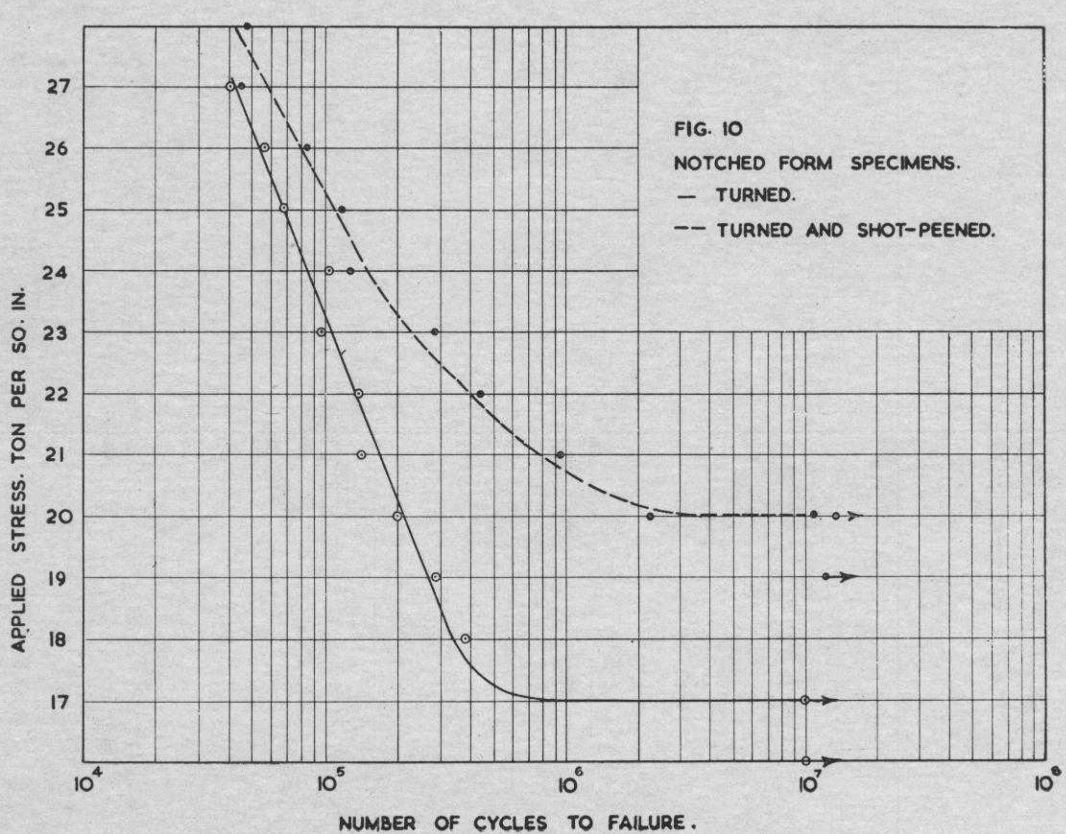
FIG. 10
NOTCHED FORM SPECIMENS.
— TURNED.
-- TURNED AND SHOT-PEENED.
APPLIED STRESS. TON PER SQ. IN.
27
26
25
24
23
22
21
20
19
18
17
10^4
10^5
10^6
10^7
10^8
NUMBER OF CYCLES TO FAILURE.

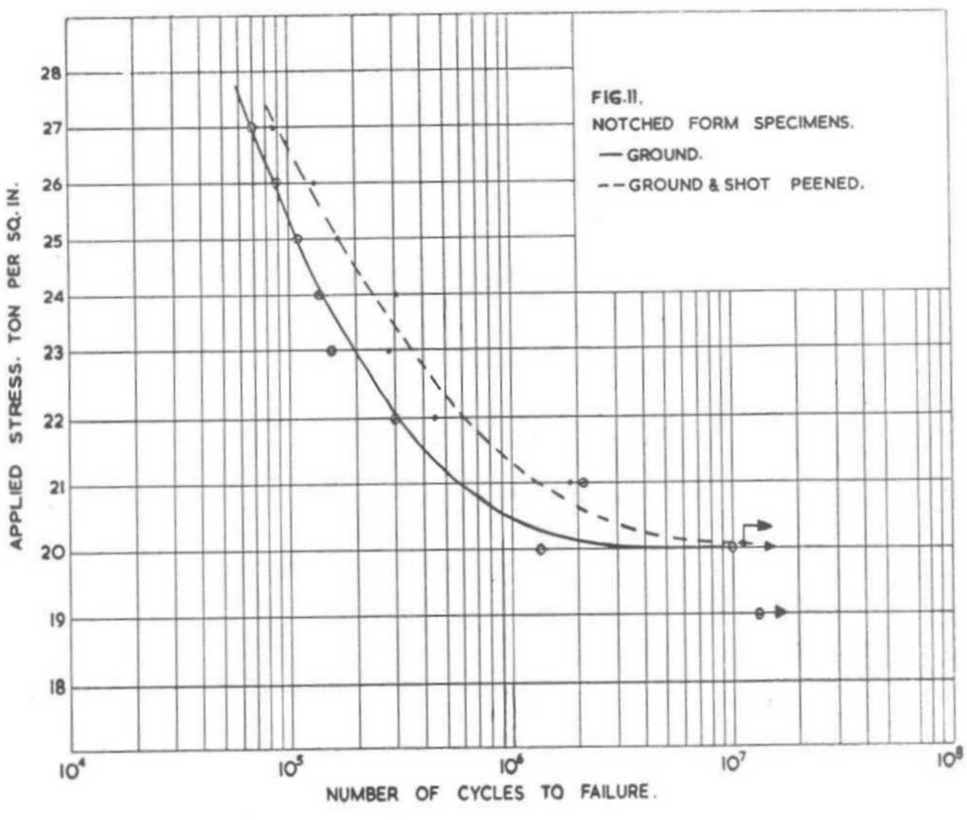
FIG.11.
NOTCHED FORM SPECIMENS.
— GROUND.
-- GROUND & SHOT PEENED.
APPLIED STRESS. TON PER SQ. IN.
28
27
26
25
24
23
22
21
20
19
18
10^4
10^5
10^6
10^7
10^8
NUMBER OF CYCLES TO FAILURE.

From these curves the following results may be derived :—

Type of Specimen	Estimated Endurance Limit	Increase in Endurance Limit Caused by Peening
	ton/sq. in.	per cent
Plain Form		
Turned surface	30	
Turned and peened surface	32	6
Ground surface	33	
Ground and peened surface	33	Nil
Notched Form		
Turned surface	17	
Turned and peened surface	20	18
Ground surface	20	
Ground and peened surface	20	Nil

If the failure region of the curves, that is, that portion above the endurance limit, be examined, the increase in life is indicated by the following figures :—

1. Turned plain specimens.
   at stress of 33 ton/sq. in. 300%
   at stress of 36 ton/sq. in. 100%
2. Ground plain specimens.
   at stress of 34 ton/sq. in. 200%
   at stress of 37 ton/sq. in. 50%
3. Turned notched specimens.
   at stress of 21 ton/sq. in. 350%
   at stress of 26 ton/sq. in. 50%
4. Ground notched specimens.
   at stress of 21 ton/sq. in, ... 150%
   at stress of 26 ton/sq. in. 50%

From these figures it is possible to draw the following conclusions :—

1. Shot-peening of turned surfaces increases the endurance limit by about 6 per cent for plain specimens and about 18 per cent for notched specimens. At stresses

slightly greater than the endurance limit, peening increases the fatigue life by something of the order of 300 to 350 per cent for both plain and notched specimens.

2. Shot-peening of ground surfaces did not significantly affect the endurance limit. At stresses slightly greater than the endurance limit peening increases the fatigue life by 150 per cent and 200 per cent for notched and plain specimens respectively.
3. The life of turned and peened specimens is comparable with that of ground and peened specimens in the failure region and the difference, if any, in the endurance limit is small. This indicates that if the final surface treatment is to include peening, very little is gained by grinding before peening.

CONCLUSION

Shot-peening can, under favourable conditions, greatly improve the resistance of metal parts to failure by fatigue. The process has been applied in many cases as a corrective measure after failures have occurred in service, but it is well worth considering during the initial design stages.[9]

There is scope for much investigational work in this field both in the direction of laboratory research as well as service trials.

ACKNOWLEDGEMENTS

This paper is published by permission of the Chief Scientist, Department of Supply, Australia.

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