

A DISCOURSE ON FACTORS WHICH CONTROL FATIGUE BEHAVIOUR IN HIGH YIELD LOW ALLOY STEEL STRUCTURES

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Abstract—In this paper the authors develop certain viewpoints which arise from experiments which have been carried out at the Naval Construction Research Establishment, to assess the low cycle fatigue properties of high yield, low alloy steel structures using standard and specially devised type tests. These relate to the way in which fatigue properties are influenced by the tensile strength and ductility; the way in which loads are applied; and the special considerations and the mode of failures peculiar to welded connections.

It is concluded that for applications which require the use of higher strength structural steels, fatigue life may be a severe limitation unless attention is paid to matters such as cleanness of steel, fabrication and means of improving resistance to fatigue crack initiation and growth.

INTRODUCTION

AN ENGINEERING structure, whatever it is made from, should be free from dangerous cracks throughout its working life. Although it is absurd to imagine a welded structure wholly free of micro cracks, and perhaps macro cracks, of one sort or another, it is important to distinguish between those which are always passive and those which might at some time become active. A crack, on reaching a critical length, may cause malfunctioning, or if the material is insufficiently notch tough, suddenly active to form a fast widespread failure comparable with the brittle fractures which afflicted so many all-welded American merchant vessels during the Second World War.

However, there have been very few serious failures, and no total failures, in riveted or welded ships made from commonly used low strength steels. Cracks which did occur as a result of overstrain or stress-corrosion, generally grew slowly and being confined to single plates it was possible for repairs to be made at convenient re-fit periods. The risk of failure due to cyclic loading, however, is greater with stronger steels which in principle have a lower life to failure for a given stress range expressed as a fraction of yield or ultimate strength. This greater risk means that more care must be taken in design and in fabrication to avoid severe stress concentration features particularly in way of welds. Thus all-welded construction and the increasing use of higher strength steels have led engineers to look for criteria which might enable fatigue to be taken into account in design.

The fatigue behaviour of structural steels indicates a general pattern of behaviour relating ultimate tensile strength, fatigue limit, severity of stress concentration and life. All steels have, within narrow limits, much the same order of fatigue limit at long life but there is a steel which has the optimum stress range for a given short life. For applications, subjected to cyclic loading, where the significance stress ranges are repeated less than 10^5 times during service life, it is thus feasible to use higher strength steels such as Q.T.35 and H.Y.80.

The extent to which even higher strength steels may be utilized, depends upon how near to the ultimate tensile strength corresponding to optimum stress range for the requisite life

AXIALLY LOADED AND BENDING TYPE TEST PIECES.

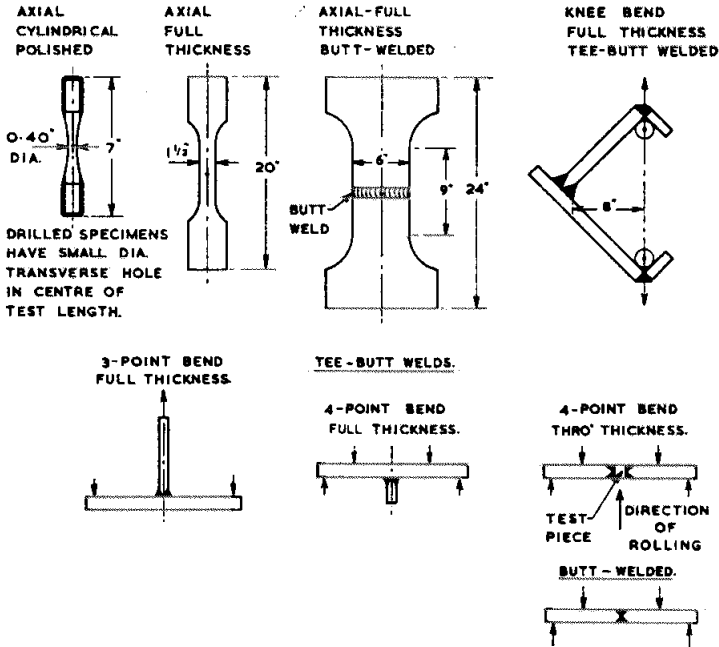


FIG. 1. Standard and type test pieces.

it is proposed to go and to what extent measures can be taken to delay the initiation of cracks at points of stress concentration by post-weld treatments, e.g. peening.

A simple generalized mechanical standpoint based on simple test pieces is useful in order to understand what is feasible in fatigue, but in practice it is necessary to adopt type testing in order to derive reliable information for designers to use. Thus test pieces representing unit full thickness parts of structures incorporating high stress features must be devised to represent the service situation realistically—ideally this means in addition a full-size replica since there is a need for correlation of information obtained from fatigue tests on full-size structures with that obtained from laboratory type test procedures.

The Naval Construction Research Establishment, over the past decade, has taken both a generalized and a practical view of the fatigue problems arising from the use of high yield, low alloy steels—principally Q.T.35 and H.Y.80—utilizing results from experimental work carried out on constant load range machines with specimens shown in Fig. 1. This has indicated important conclusions relating to factors such as tensile strength, Y/U.T.S. ratio, ductility criteria, loading method, stress concentration, welded connections and mode of failure. The present discourse outlines this work.

FATIGUE PROPERTIES OF STEELS FROM THE
SIMPLE MECHANICAL STANDPOINT

In order to understand the principles underlying fatigue behaviour of structural steels it is instructive to study the patterns of behaviour resulting from fatigue and tensile tests on steels in the range mild to maraging steel.

Figures 2 and 3 show the patterns obtained utilizing British Standard specimens tested

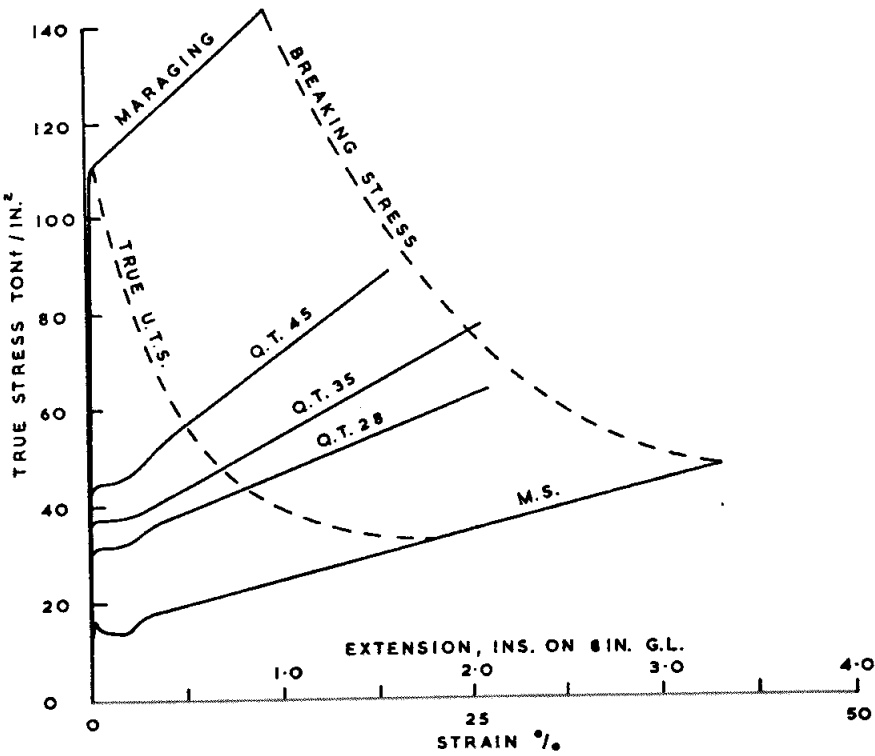


FIG. 2. True stress/strain relationships for mild and alloy structural steels.

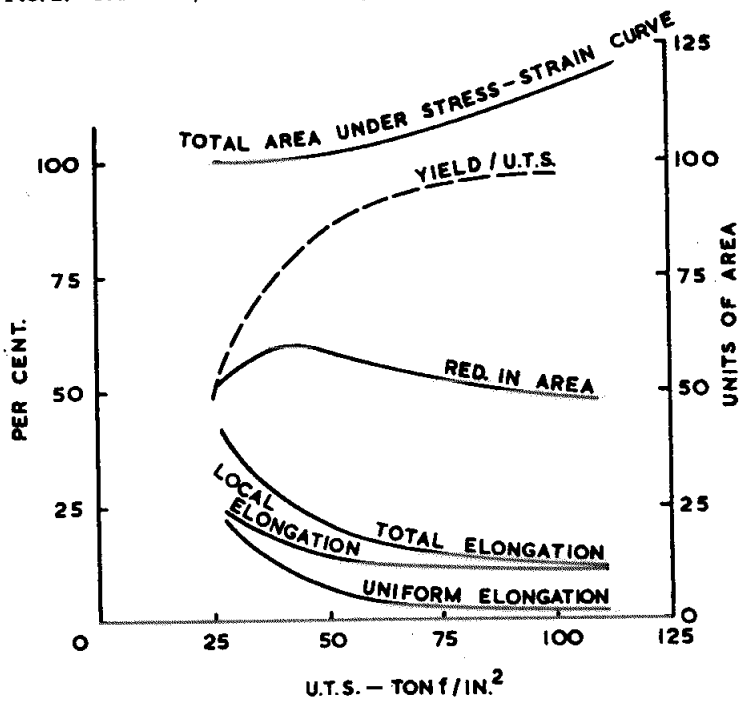


FIG. 3. Variations in ductility in tensile tests with U.T.S. for structural steels.

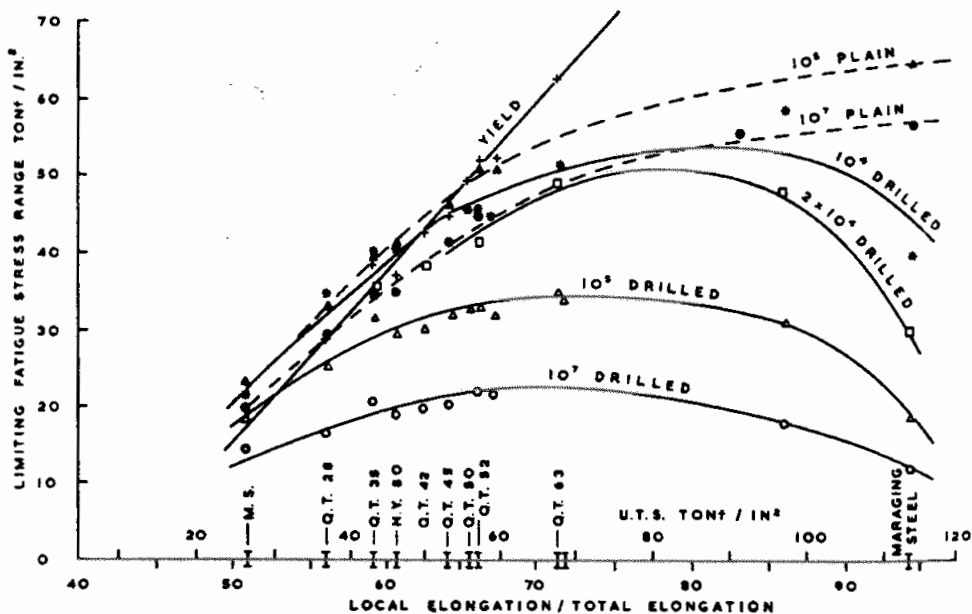


FIG. 4. Limiting fatigue stress range/U.T.S. for zero-tension cycle.

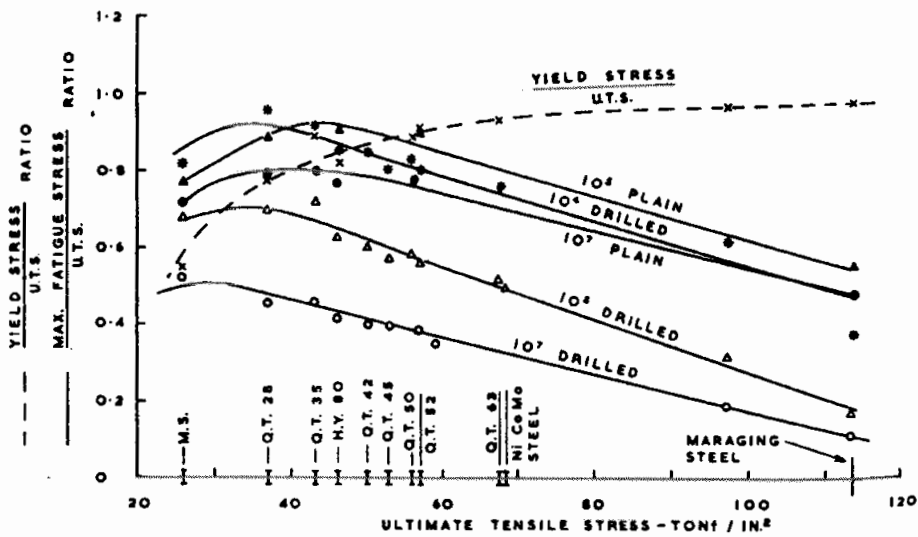


FIG. 5. $\frac{\text{Limiting fatigue stress range}}{\text{U.T.S.}}$ for zero-tension cycle.

in standard tensile testing machines; Figs. 4-6 show the patterns obtained utilizing diamond polished plain and drilled fatigue specimens tested in axial zero-tension at 50c/s. Figure 1 shows the size of specimen used. Table 1 lists the mechanical properties obtained in the tensile tests and relevant specification data. Although only one stress range (zero-tension) and one size of drilled hole, i.e. geometric, stress concentration factor, were used in forming these patterns a number of conclusions may be drawn.

TABLE 1. MECHANICAL PROPERTIES AND CHEMICAL COMPOSITIONS OF MATERIALS USED FOR FATIGUE TESTS

Material	0.2% proof stress or yield stress tonf/in. ^a	Ultimate tensile stress tonf/in. ^a	Yield U.T.S.	Chemical composition												
				C	Si	Mn	S	P	Ni	Mo	Co	Cr	Ti	Al	V	
Mild steel	14.3	26.3	0.54	0.15	0.06	0.50	0.032	0.015	0.07	Mo+V <0.02	<0.05					See Mo
Q.T.28	28.2	36.8	0.77	0.15	0.05	1.25	0.026	0.022	0.30	0.26	0.15	0.02	0.005	0.03		
Q.T.35	38.4	43.0	0.89	0.12	0.21	0.88	0.016	0.021	1.04	0.45	0.93					
H.Y.80	37.5	46.0	0.82	0.16	0.17	0.30	0.014	0.009	2.77	0.44	1.29					0.03
Q.T.50*	49.5	55.7	0.89	0.22	0.08	1.11	0.026	0.012	1.25	0.55	0.93		<0.01	0.06		
Q.T.52*	52.0	58.0	0.90	0.21	0.22	1.05	0.026	0.026	1.05	0.54	0.94					0.09
Q.T.63*	62.8	67.5	0.93	0.16	0.17	0.30	0.014	0.009	2.77	0.44	1.29					0.03
H.Y.80 (Heat treated)	—	—	—	—	—	—	—	—	—	—	—					—
Maraging steel Normalized (British)	50.5	68.4	0.74	0.03	0.10	0.05	0.014	0.010	17.52	5.0	7.6		0.42	0.055		
Maraging steel Heat treated (British)	111.2	113.6	0.98	0.03	0.10	0.05	0.014	0.010	17.52	5.0	7.6		0.42	0.055		
Maraging steel Heat treated (Canadian)	95.0	97.7	0.98	0.016	0.10	0.02	0.008	0.004	19.25	4.25	8.15	<0.01	0.37	0.054		

*Special heats

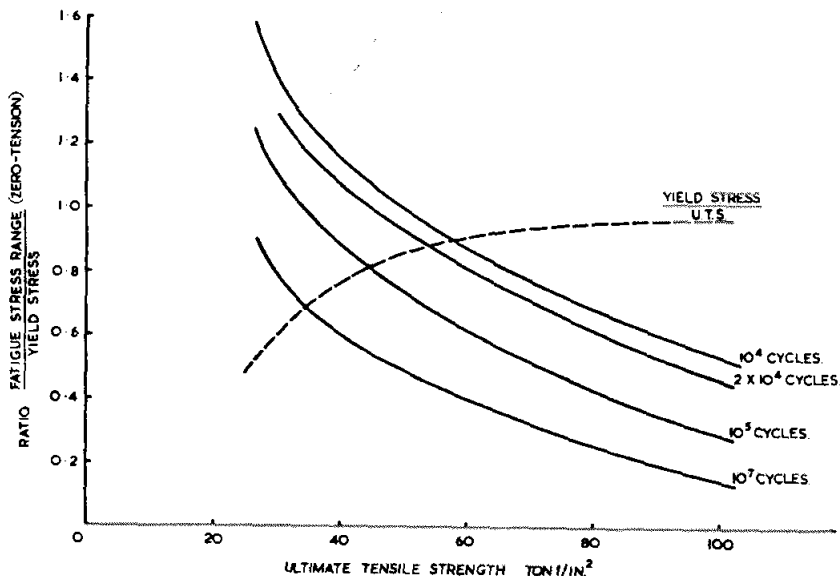


FIG. 6. Limitations of design stress in relation to yield for structural steels based on a given fatigue life (zero-tension cycle) for drilled specimens.

Tensile

- Increase in the U.T.S. means a decrease in the strain to failure and an increase in the mean slope of the stress-strain curve beyond yield.
- The post-yield strain at U.T.S. becomes very small with higher strength steels.
- The post-ultimate strain to failure, representing that in the necked portion of the specimen, decreases and becomes progressively more localized with increase in U.T.S.
- A change in character in the relationships between ductility with U.T.S. occurs at U.T.S. of 50–60 tonf/in.²
- Only moderate changes occur in the reduction of area of specimens at the fractured neck, and in the total energy absorbed in fracture, for the range of steels considered.

Fatigue

- For steels up to about 70 tonf/in.² U.T.S. it is possible to fit approximately linear relationships between limiting fatigue stress range (zero-tension) and U.T.S. Similarly, for higher strength steel it may be possible to fit such relationships: in plain specimens the gradient is less but there is a significant change from positive to negative in the case of drilled specimens.
- The plain and drilled results lie in two distinct bands.
- A distinct pattern holds if the fatigue stress ranges are expressed as a ratio of U.T.S.
- Advantage can be taken of the higher strength steels incorporating severe stress concentration at short life and there is an optimum U.T.S. for a given life to failure.
- The ratio $\frac{\text{fatigue stress}}{\text{yield stress}}$ changes with increase in U.T.S. in drilled specimens for given lives to failure in such a way that the same advantage cannot be taken of yield point in higher steels as in mild steels.

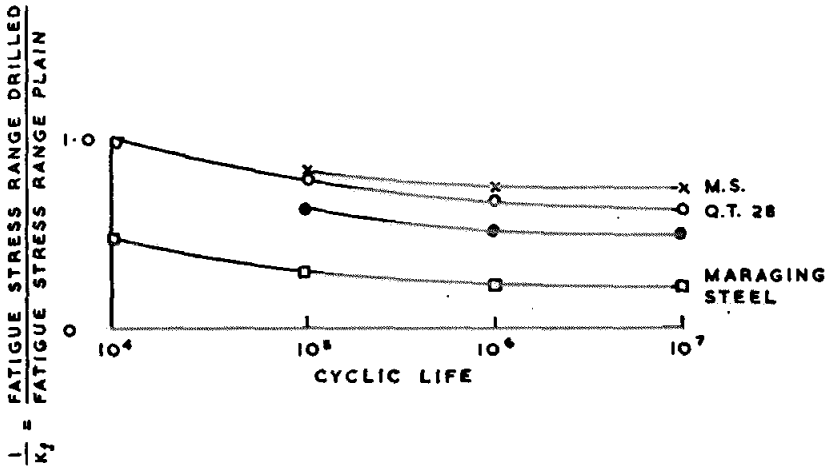


FIG. 7. Fatigue stress reduction factors for structural steels over range 10^4 - 10^7 cycles.

(f) Taking the effective limiting fatigue stress reduction factor

$$k_f = \frac{\text{fatigue stress range in plain condition}}{\text{fatigue stress range in drilled condition}}$$

it can be seen from Fig. 7 that k_f increases with increase in U.T.S. and increase in cyclic life. The negative slope of the curves in Fig. 4 for drilled higher strength steel specimens results from the increase in k_f .

Although it is generally accepted that ferrous materials all have much the same fatigue life for the same range of strain it nevertheless follows that a higher strength material has a greater load-carrying capacity for strains which would exceed the elastic limit of a lower strength steel. At a stress concentration, such as the drilled hole used in this investigation, it is difficult to appreciate exactly what is happening no matter whether it is the nominal cyclic load or strain that is kept constant.

The results for the drilled specimens relate to a hole approximately $\frac{1}{32}$ in. (see Fig. 1) diameter and it is to be expected that any reduction in the hole size would further reduce life to failure. Indeed, Welding Institute have shown that a sharp circumferential scratch results in materials such as BS15, BS968 and Q.T.35 having much the same fatigue limit for lives greater than 10^5 cycles (Signes *et al.* 1967).

The results indicate that the limiting fatigue strength of mild and high strength structural steels in axial-zero-tension tests can be allied to properties devised from simple tensile tests even though the micro-mechanisms of failure appear to differ. There would appear to be a strong link between fatigue strength and mechanical properties such as Y/U.T.S. ratio and uniform elongation of the gauge length which is sustained up to U.T.S. Present structural steels of weldable quality (including Q.T.35 H.Y.80) have much the same endurance ratio (fatigue stress range to failure)

$$\frac{\text{fatigue stress range to failure}}{\text{U.T.S.}}$$

for a given life: the value being dependent upon the severity of any stress concentration present. However, since it is necessary to base design stress upon yield stress, and since Y/U.T.S. ratio increases with U.T.S. it follows that for the same criterion of $\frac{\text{design stress}}{\text{yield stress}}$ the life to failure decreases with increase in U.T.S.

The usual concepts of design cannot apply to very high strength steels in way of a notch. On the basis of present results, which most likely overestimate life in practical structures, a factor of safety on nominal load of 5:1 applied to a 115tonf/in². U.T.S. steel would not give an indefinite fatigue life if a notch were present. At short life of say 10⁴ cycles such a steel would be no better than one-half its ultimate tensile strength. At long life it would only equal the performance of mild steel. There would appear to be an optimum strength in relation to ductility and fatigue resistance for a given life to failure.

Thus by a simple consideration of standard test results it is possible to get a broad picture of fatigue behaviour as it affects the structural engineer. It is of course limited in that it does not take into account factors introduced by welding and factors consequent upon the introduction of locked-in strains adjacent to welds.

FACTORS WHICH COMPLICATE THE SIMPLE MECHANICAL STANDPOINT

The effect of an abrupt change in shape on fatigue behaviour was outlined in the last section. The acuity of the change, which may be a minute but sharp scratch or a gradual contour, affects the local concentration of strain, and hence stress, during the application of a nominal load to the whole section. In the first place if no yield occurs at the stress concentration the local mean stress and cyclic stress ranges are increased according to the value of the geometric stress concentration. In the second place, if yield does occur, the local mean stress of the cycle is affected by the inelastic behaviour: this is illustrated as follows assuming that the upper limit of the cyclic stress Y is the yield stress. If the nominal uniformly applied cyclic stress range is R , the local stress concentration factor is C and the local mean stress is M .

$$\text{Then } M = \frac{1}{2} [Y + (Y - CR)]. \quad (1)$$

For the case of $R = \frac{1}{2}Y$ and no stress concentration (i.e. $C = 1$)

$$M = \frac{3}{4}Y.$$

For the case of $R = \frac{1}{2}Y$ and stress concentration factor $C = 2$

$$M = \frac{Y}{2}.$$

Thus in this particular case the local mean stress at the stress concentration is lowered.

In an opening crack, fatigue action can only result if there is a tensile stress component normal to the path of the crack. This component may well arise from the net tensile local mean stress even though the applied cyclic stress range is wholly compressive, so that it is possible for cracks to develop even under nominally compressive stress ranges, e.g. in a welded connection.

This mean stress can have an important bearing on the life to failure as indicated in Fig. 8 where the fatigue range is plotted non-dimensionally against values of compressive and tensile mean stress. In these diagrams it can be seen that all values of zero to tension, or zero to compression, are at 45° to base through the axis. Lines representing constant yield, or U.T.S. subtend angles of 45° to both coordinate axes and so form the closing sides of right-angled triangles. At a given life there is a definite decrease in cyclic stress range with increase in tensile mean stress and this decrease becomes more pronounced at higher values of mean stress or at shorter life. At long life this decrease is less marked, especially for drilled specimens. This behaviour is in contrast to the definite increase in cyclic stress range with increase in compressive mean stress. If the cyclic range is zero to just below yield in compression no failures evidently occur even at long life, unless buckling takes place, although cracks may develop for a small distance from stress concentrations. It is noteworthy that a

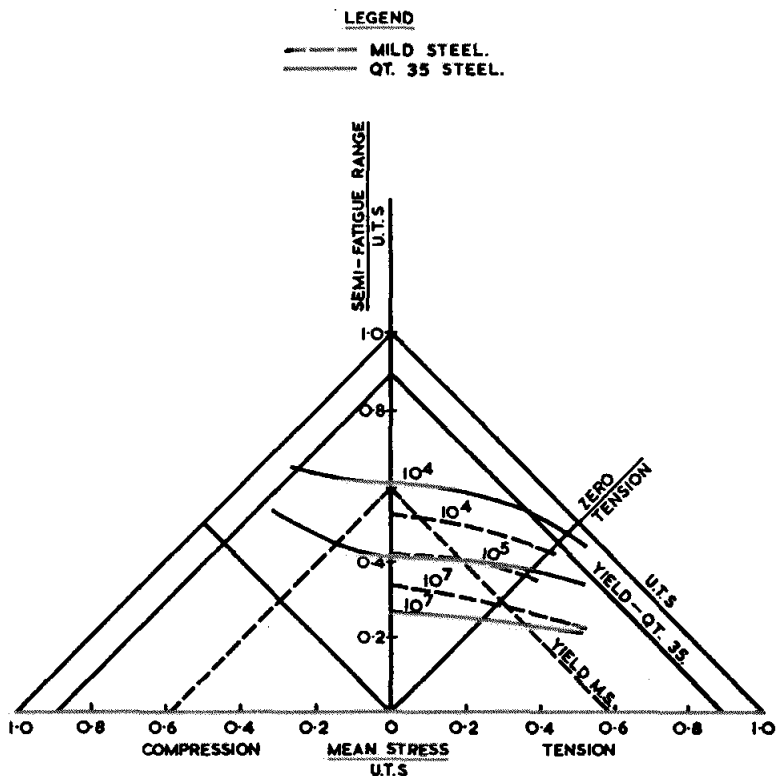


FIG. 8. S-M diagram for mild steel and Q.T.35 steel.

point of inflexion in the cyclic stress mean stress relationship occurs at about zero mean stress and it is often reasonable to neglect the effect of small changes in mean stress on the fatigue life. However, in way of a stress concentration, there may be considerable local changes in mean stress.

As indicated above it is possible to get limited crack development from a stress concentration even though the nominal cyclic stress range is wholly compressive if tensile components are set up. This was in fact found to be the case in a specimen subjected to a nominal axial zero to compression cycle where the maximum stress approached yield in compression. By (1), assuming $C = 2.2$, it is easy to see that the actual range of elastic stress induced at the edge of the hole should be over twice yield. However the maximum stress is virtually limited to yield. During the unloading part of the cycle there will be a strain relaxation at the edge of the hole, equal to over twice yield and this reverse strain thus gives rise to tensile plastic strain. In subsequent cycles the edge of the hole alternates between tensile and compressive plastic strain: there is likely to be a wide hysteresis loop: cracks soon develop. However, as they spread, the faying surfaces come together during part of the cycle and effectively decrease the strain range at the crack front. Thus there is a progressively smaller opening of the crack faces and growth of the crack ceases since the stress during the tension epoch of the cycle drops below the limiting fatigue range. In the actual test 0.02in.-long cracks were evident after 5.5×10^4 cycles and these grew to 0.04in. after 70×10^4 cycles. By then the amplitude of crack opening had lessened. The cracks grew to 0.05in. after 337×10^4 cycles but remained at this length until 3200×10^4 cycles when the test was

stopped. This action can be contrasted with that of a specimen similarly loaded in tension where no such relief of strain occurs at the crack front.

The manner in which fatigue stress range falls with increase in mean stress suggests that at the long life fatigue limit the maximum stress at which yielding would occur at the edge of the hole increases with U.T.S. Thus the full effects of the elastic stress concentrations are reduced by plastic yielding in the case of mild steel resulting in a lowering of the mean stress, whereas the high mean stress is maintained in the case of the high yield steels. The effect of the latter action is to reduce the long life fatigue strength of high strength steels to much the same level as that of mild steel: ultra high strength steels appear to be worse in Fig. 4 (Haigh (1929)).

The above considerations illustrate what can happen if the maximum stress is limited to yield. They do not, however, take into account the local strains which are developed nor what might happen if the stresses were not limited to yield. To do this would involve a much more complicated analysis for which very precise micro measurements would have to be obtained. At present it is only possible to infer most generally what is happening and what the simple experiments outlined in this section, and the last, amount to in answering the most general and vital question as to how to improve fatigue strength of higher strength structural steels in way of a notch.

A key to this improvement would appear to lie in the shape of the true stress-strain diagram in simple tension. The steeper the stress-strain curve between yield and U.T.S. for a given applied nominal strain, the greater the initial stress concentration factor in the plastic zone at the edge of a drilled hole: and for a given applied nominal stress the more limited the extent of the localized plastic zone. If this be the case it might be inferred that fatigue action at a notch is more intense in high strength material. Such matters must affect the initiation and the rate of propagation of cracks and the equations relating stress or strain level, cyclic life and crack length. If it is assumed that fatigue action either at initiation or during propagation, is in essence a matter of localized cumulative exhaustion of potential energy related to tensile ductility, it follows that materials which have a higher resistance to fatigue crack initiation at machined notches are likely to have a slower rate of crack growth under given conditions of loading. Beyond this it is necessary to examine the fundamental behaviour on a more sophisticated physical basis. It is this basis which should now be attracting most attention if significant strides in material development for aerospace and submarine applications presently under way, are required.

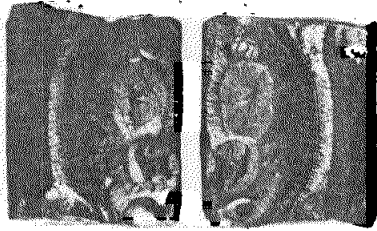
FACTORS WHICH COMPLICATE THE WELDED JOINT

In the last section it was pointed out that even in the case of a plain piece of steel containing a notch there were complicating factors which, although understood generally, left much to the imagination with respect to what really happens in a fatigue test. From Fig. 3 it can be seen that the applied stress plus any residual stress due to fabrication clearly cannot exceed much more than half the U.T.S. for mild steel but might easily reach 0.9 U.T.S. in Q.T.35.

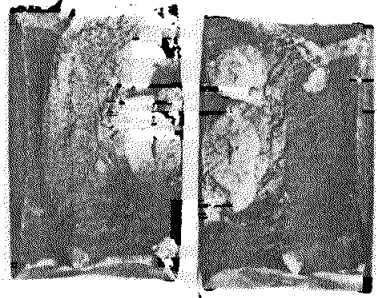
In welded joints, defects and inclusions form internal stress concentrations in addition to any external geometric discontinuities. Some idea of their possible effect can be discerned from the results of axial fatigue tests on specimens containing a small transverse hole or a circumferential groove. Although such holes cannot be supposed to be generally representative of all defects it is possible that the stress concentration factor is sufficiently high to represent more serious welding defects. Figure 9 shows a photograph of such a defect in a

Transverse butt welds

(a) Slag inclusion.

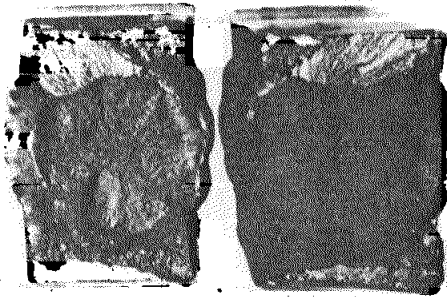


(b) Slag inclusion



Longitudinal butt weld

(c) Slag inclusion



Plain specimen

(d) Transverse drilled hole

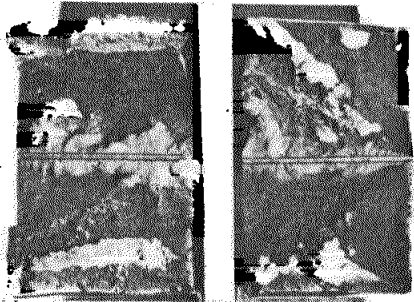


FIG. 9. Fatigue fractures initiated by defects in butt-welds.

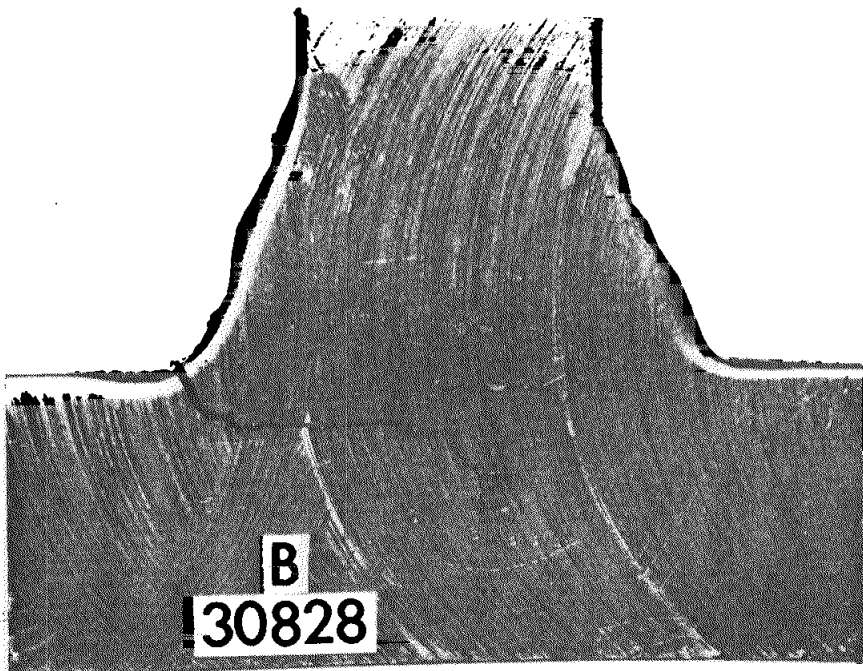


FIG. 11. Short transverse stepped fracture.

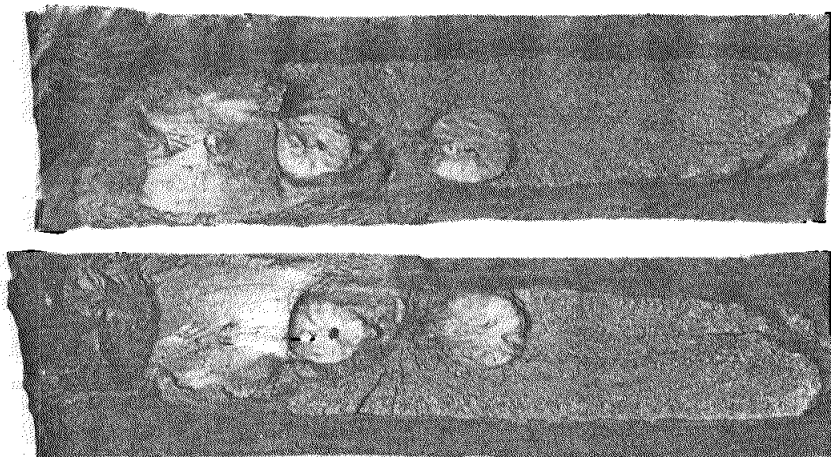


FIG. 14. Fatigue crack initiated at weld inclusions in butt-weld (smooth light-coloured areas). Resulted in a brittle type fracture (crystalline area).

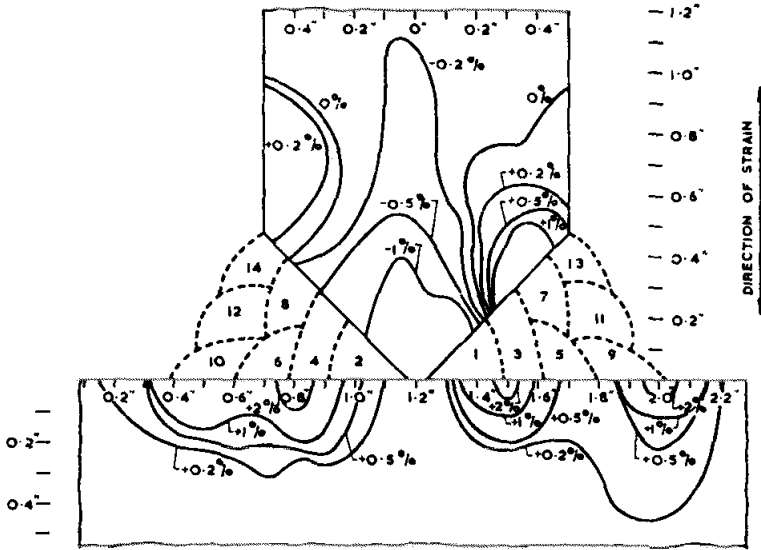


FIG. 10. Strain distribution in a tee-butt weld.

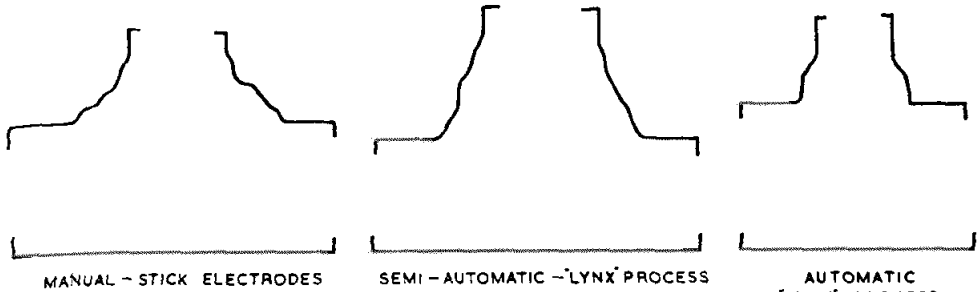


FIG. 12. Range of tee-butt weld profiles.

transverse butt-welded specimen 1½ in. thick and 2 in. wide from which a fatigue crack developed finally leading to ductile failure. Figure 9 also shows a fatigue fracture which developed from a drilled specimen.

Superimposed on the surface and within the welded joint are stresses resulting from the cumulative strains arising from shrinkage of welded deposits on solidification and cooling which will be greater in high strength welds and depend upon the elastic compliance of the adjacent structure. The value of this pre-stress varies over the welded joint, satisfying the principle of equilibrium of forces and moments. At the surface the result of welding is usually to set up biaxial tensile stresses. Figure 10 shows examples of strains set up by welding under a tee-butt weld obtained by a Moiré fringe technique (Cargill, in press). The interaction of such factors is of course most complex and in tee-butt welds may be further complicated by the presence of non-metallic inclusions which are arrayed in lamellar form parallel to the plate surface during rolling unless steps are taken to avoid them in steel production. These inclusions, if of critical size and number, can influence the mode of failure in fatigue tests if sufficient load is transmitted through the joint. A lamellar tear,

called a short transverse crack, which is quasi brittle can result as shown in Fig. 11 (Thompson *et al.* (1968)).

Such inclusions are likely to be subjected to normal loads which are much greater in higher strength steel than in mild steel. For a given toughness, therefore, it follows from the simple Griffith relation $\sigma^2 C = K$ that the critical crack length of an inclusion is inversely proportional to the square of the normal stress. Even though it may be hypothetical to apply this reasoning to short transverse fracture, which is only quasi-brittle, it is instructive to do so. Since the designer of a structure wishes to take full advantage of strength, the working stress may be regarded as proportional to the yield stress. Thus on the assumption that K does not vary much between structural steels the critical crack length in Q.T.35 (see Table 1) for fracture at yield stress would be a little over one-ninth the size of that in mild steel. If the distribution were such that a $\frac{1}{10}$ in.-long defect was critical in mild steel then this would correspond to 1/100in.-long defect in H.Y.130 and only 1/200in. defect in 120 tonf/in.² yield steel. Although differences in K for various steels will modify this, the conclusion that higher strength steels are likely to have considerably smaller critical crack lengths is valid; thus there may be a risk of fast fracture, in addition to limitations of fatigue strength if the critical lengths are exceeded.

The significance of small inclusions in Q.T.35 thus arises because of the combined effect of three factors, namely,

- (a) the high yield stress to ultimate stress ratio and consequently the higher design stress to ultimate stress ratio used,
- (b) the higher residual stresses and strains set up by the contraction of weld metal on solidification,
- (c) the type and size of the non-metallic inclusions which may for instance be sharp-pointed silicate or disk-like sulphide.

In electric furnace H.Y.80, which was relatively free from such inclusions, fatigue cracks which developed in three-point and knee-bend specimens propagated at right angles to plate surface: in open hearth Q.T.35 used, which was much dirtier than the H.Y.80, failure often occurred along lamellar planes.

FACTORS WHICH MAY ENHANCE THE FATIGUE STRENGTH

The simple mechanical considerations and the factors relating to welded joints make it imperative to seek ways and means of improving fatigue strength of these connections. There are a variety of things that may be done, for instance, the weld contour can be improved, the state of stress and strain at the surface can be beneficially changed: these improvements can be achieved mechanically, by thermal treatment or by attending to welding techniques. At N.C.R.E. it has been found that the most effective method, by far, is mechanical peening (see appendix).

Mechanical peening, judiciously applied, delays crack initiation in low-cycle fatigue tests on welded joints when the peening is applied at the weld/plate intersection, which is subject to combined tension and bending. This delayed initiation is thought to be due to:

- (a) induced local work hardening in elastic restrained material,
- (b) induced compressive residual stresses due to local plastic deformation,
- (c) attrition of microstructure causing cracks to take devious paths during early development,
- (d) better geometric transition at weld/plate intersection.

Peening can be used to arrest cracks which are shallow. The peening operation puts the

peened surface into compression with respect to curvature of indentation and equilibrium is maintained by tensile stresses of smaller magnitude further away into material: there is no evidence to suggest such tensile stresses cause cracks. It is possible for lamellar tears to be opened up in dirty steels if mechanical peening procedure is too rigorous. However, it appears that fatigue resistance is not adversely affected. It is likely that even if small surface cracks in the deformed area do result from peening they arrest on running into zones of subcritical cold work. Peening would be very beneficial if it delayed crack initiation in very high strength steels.

THE DEVELOPMENT OF TYPE TEST PROCEDURES

In determining the fatigue properties of welded joints realistically, it is necessary to take into account the overall properties of base plate and weld metal, the built-in strains induced and stress concentrations resulting from external shape of weld and internal flaws. In tee-butt welded joints it is also necessary to take into account the strength and ductility of base plate material and heat-affected zones in the short transverse direction since in conventional structural steels these may be less than in the longitudinal or transverse directions. Although it may be possible, as outlined in the previous sections, to account for the effects on fatigue properties brought about by stress concentrations and built-in stresses as such, it is impracticable to synthesize exactly what is happening in a full thickness welded joint. For this reason it is necessary to use type test procedures. Such procedures are only of value if they can effectively do one of two things.

- (a) Predict quantitatively the initiation and propagation of fatigue failure in a service structure.
- (b) Indicate in a qualitative manner features of materials and fabrication processes which will significantly affect the life of the structure.

First thoughts might suggest that the ideal type test is a full-size test where all the conditions likely to be met with in service are introduced. This would require considerable expense and a long time. The results from such a test would not necessarily be applicable to any other large structure where the design details differed. Also there may be uncertainties with regard to long-time effects brought about by ageing, speed and programme of cycling, corrosion and consequent cumulative damage. Even so, a full-size test would give some confidence, or alarm, and if the growth of cracks extended over long periods of time it might be possible to introduce detailed changes in material or fabrication with a view to improving performance. To some extent every structure that is built presents an opportunity for a full-scale type test but it is not usually possible to follow in sufficient details all the changes which might occur in order to classify what has happened: discovery of cracks usually leads to repairs as soon as possible. Full-scale, or near full-scale, facilities do exist, e.g. for prototype aircraft and pressure vessels.

At N.C.R.E. it was realized that, in large steel structures there would undoubtedly be weak spots at welded connections and that it was necessary to examine the behaviour of full thickness test pieces resembling such connections under simple uniaxial loading conditions in the laboratory. In this way much could be learned as to how cracks initiated and grew at selected levels of loading even though the tests could not entirely simulate the true effects of biaxial loading or elastic restraint. It was possible to compare the results from one such series of tests with the performance of an actual unit of structure subject to internal cyclic pressure.

Figure 1 indicates the form of the various type test specimens devised for testing at constant local ranges and constant cyclic speed.

- (a) Tensile and compressive test specimens.
- (b) Three and four-point bending tests on simply supported bars.
- (c) Knee-bending tests.

The loading configuration used in (b) and (c) give quite different ratios of $\frac{\text{direct stress}}{\text{bending stress}}$ at the weld/plate intersections of tee-butt welded joints. During the course of the experimental investigations it was considered that a representative type of specimen for comparative tests on different tee-butt welded joints would be the three-point bend type in which the nominal $\frac{\text{direct stress}}{\text{bending stress}}$ ratio could easily be varied: a ratio of 1/10 and a constant nominal stress range of 30tonf/in.² at weld/plate intersection were selected.

The methods used to load the specimens were carefully selected to get good alignment in the testing machine and to ensure that a uniform transverse stress distribution was applied along the length of the weld at the weld plate intersection. A cyclic speed of 25c/min was used for most tests. Earlier tests on axially loaded specimens at other speeds in range $\frac{1}{2}$ c/min to 400c/min had indicated that it was desirable to adopt as low a speed as was practicable. A lateral strain ranging from zero at the edge of the specimen to a maximum at mid-length was induced by bending. The actual sizes of the specimens were restricted to suit the load capacity of the available pulsators but were large enough to contain residual stresses and strains which, although perhaps different from that in actual structures, go some way towards realism.

In order to observe the incidence and growth of cracks, a watch-keeping system was operated by which observations were made at suitable intervals of time. The watchkeeper found that visual assessment of crack length was aided if a thin film of light machine oil was smeared on to the specimen and the test surface viewed under oblique lighting. Ultrasonic examination was sometimes used to follow crack development but this was not possible for all specimens owing to the time-consuming nature of this technique.

In this work the emphasis has been placed on low-cycle properties for lives up to 10⁴ cycles using four criteria of assessment, viz. crack at initiation, full weld width crack, final failure and fracture mode, i.e. normal or short transverse. The onset of failure can be observed with a fair degree of accuracy by the visual method used at N.C.R.E. or by the use of more sophisticated techniques involving ultrasonic equipment or eddy current detectors. The propagation of fatigue cracks along the weld/plate intersection can also be detected by both methods. The number of cycles to crack initiation and full width of test piece must reflect the severity of the stress concentration, the residual stress conditions and the ductility of the deposited metal.

THE TYPE TEST BEHAVIOUR OF WELDED JOINTS MADE FOR Q.T.35 AND H.Y.80

The importance placed on type testing procedures naturally led to an extensive programme of tests aimed at predicting quantitatively the order of life to initiation and the rate of crack propagation to failure that might be expected in a full-size structure. The work has covered a variety of test pieces mentioned in the last section, steels, welding processes and post-weld treatments of interest to the Naval Constructor.

The material used in that part of the investigation which is described in this paper was

either Q.T.35 or H.Y.80, generally in 1½ in.-thick plate but including some material in range 1-2 in. thickness. Details of typical steels used including chemical analyses and mechanical properties are given in Table 2. The welded joints were made according to the appropriate procedures laid down for British shipyards. These procedures included manual and semi-automatic processes resulting in different weld profiles, typical examples of which are shown in Fig. 12. All tee-butt welded joints were examined using appropriate ultrasonic techniques in order to ensure freedom from serious weld defects or lamellar tears, except where these were specifically left in. All plain butt welds were examined using appropriate radiographic techniques to ensure freedom from serious weld defects.

TABLE 2. MECHANICAL PROPERTIES AND INCLUSION COUNTS FOR TYPICAL Q.T.35 AND H.Y.80 STEEL USED IN TYPE TESTS

Steel	L, X or S.T.	Results from No. 12 size Hounsfield tensile tests				N.C.R.E. inclusion count			
		Yield tonf/in. ²	U.T.S. tonf/in. ²	Elong %	R in A %	Silicate	Sulphide	Alumina	Total
QT.35	L	42.1	47.6	27	75	2.6	2.4	—	5.0
	X	42.1	47.6	24	62				
	S.T.	42.1	45.9	8	5				
HY.80	L	31.6	39.2	27	75	—	0.6	0.1	0.7
	X	32.0	40.0	30	79				
	S.T.	32.3	39.7	21	50.5				

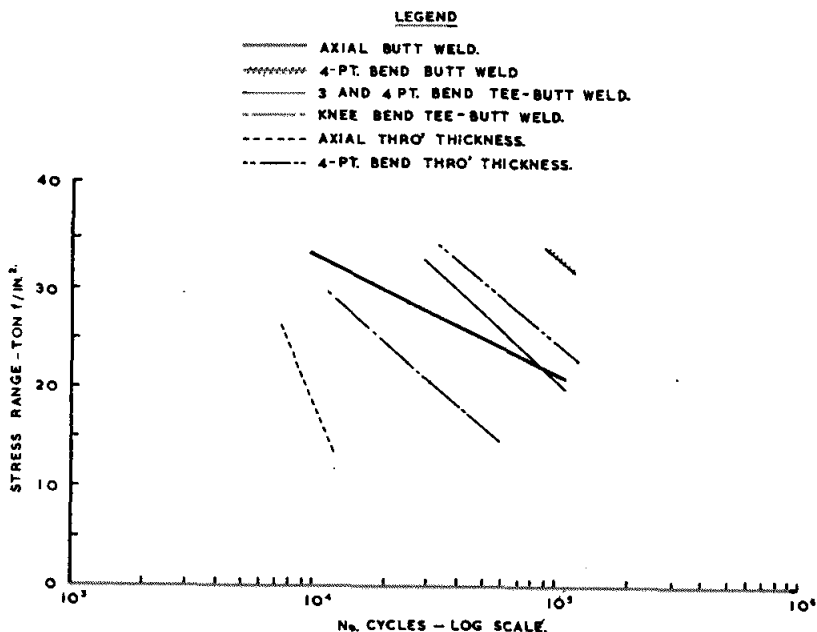


FIG. 13. Generalized results from Q.T.35 type tests (zero-tension stress cycles).

Generalized pattern of type test results

Figure 13 shows the generalized pattern of type test results for Q.T.35 plate specimens welded with the same weld metal from nominally zero-tension fatigue tests. The lives are those for final failure of the test piece. Included are results from:

- (a) Full thickness plate loaded axially, in short transverse direction and in four-point bending.
- (b) Tee-butt welds loaded in three-point, four-point and knee-bending.
- (c) Butt-welded specimens loaded in axial and four-point bending.

The stresses in Fig. 13 refer to nominal tensile stress range for axial specimens and stresses at weld/plate intersection calculated from the applied loads for the bending specimens.

It can be seen that the specimens incorporating full thickness plate and subject to uniform axial loading in the short transverse direction have given the poorest performances. Failure in these tests was induced by lamellar non-metallic inclusions (sharp-pointed silicate, disk-like sulphide) which were of sufficient length, and were present in sufficient concentration to reduce the inherent ductility and give rise to a stepped fracture appearance (see Fig. 11). The effect of lamellar inclusions in weakening the fatigue strength also manifests itself in the knee-bending tests where a crack on initiation at plate/weld intersection is subject to tensile opening forces normal to plate surface. This effect of lamellar inclusions would not be expected to be so significant in four-point bend tests where the plate surface or the tee-butt weld is subject to a bending moment only and would be expected to be significant in three-point bend tests only if the $\frac{\text{direct stress}}{\text{bending stress}}$ ratio at the tee-butt weld was high enough.

The results for the axially loaded butt welds, which had the welding reinforcements ground off, were influenced by the presence of internal or external defects. Such defects can clearly give rise to a wide scatter in results, particularly if they lead to brittle behaviour.

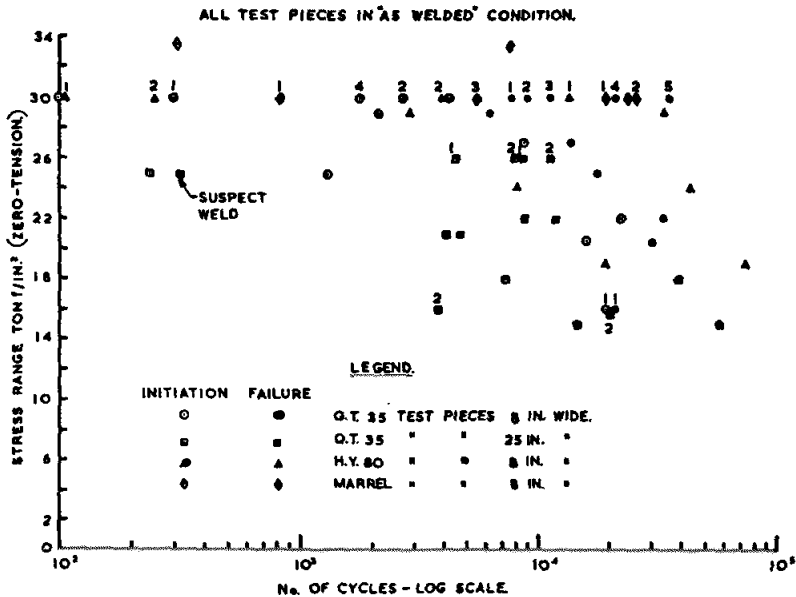


FIG. 15. H.Y.80, marrel and Q.T.35 steel knee-bend test results.

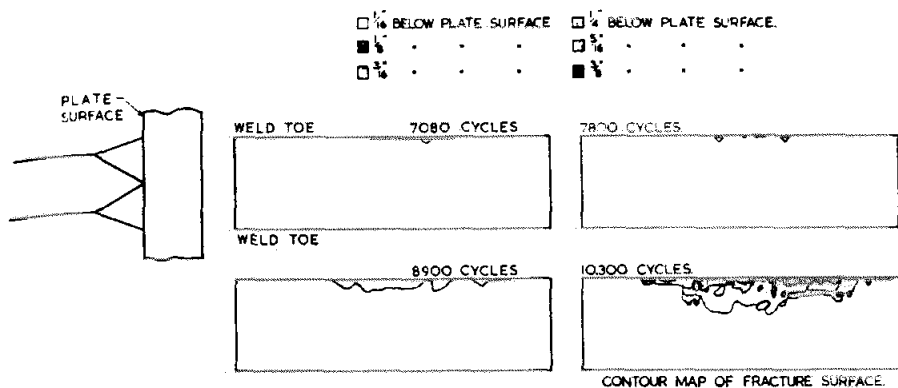


FIG. 16. Rate of fatigue crack growth under weld, in short transverse mode, in knee-bend test piece.

Figure 14 shows a photograph of a failure of this kind which occurred after a very short life. Failures which started from internal defects in fusion zones of welds gave rise to bright haloes of fine texture which ceased to develop when they broke surface and gave way to a more usual type of appearance. This halo is thought to be associated with diffusion of hydrogen leading to low-energy fracture. In general it can be seen that with butt welds and short transverse specimens, failure occurred later in four-point bend tests than in biaxial tests.

Results from knee type tests

Figure 15 indicates the trends in results obtained from zero-tension tests on 8in.-wide knee type specimens made from Q.T.35 and H.Y.80. The lives at initiation for both materials lay in the same scatter band but at failure the H.Y.80 specimens gave somewhat longer lives. All the H.Y.80 specimens eventually failed normal to plate surface from weld/plate intersection, even though cracks in some specimens followed the weld/plate fusion zone for a substantial part of the life. In contrast the Q.T.35 specimens made from much dirtier plate all failed under the tee-butt weld in a short transverse manner, one of them after a very short life indeed. Figure 16 shows how stages in the growth of a short transverse fatigue crack in a knee specimen were mapped by ultrasonic examinations. It is not difficult to imagine a situation whereby lack of notch toughness at the toe of the weld allied to short transverse failure could result in very early failure if the non-metallic inclusions were very large.

Results from three-point bend tests

Figure 17 shows the results obtained from three-point bend specimens tested at a stress range of 30tonf/in.² at the weld/plate intersection. Q.T.35 specimens as welded, toe ground, as received welds heat treated for 1hr at 650°C and Toe peened specimens (see appendix) are included. As-welded H.Y.80 specimens are also included. All the welds were manually deposited using Fortrex B electrodes. The criteria of initiation of cracks along weld, growth to full width and final failure have been adopted. The scatter of results to final failure of a variety of welds are shown in Fig. 18. The scatter of results shown covers the number of specimens indicated.

An important finding is that mechanical peening carried out as described in the appendix

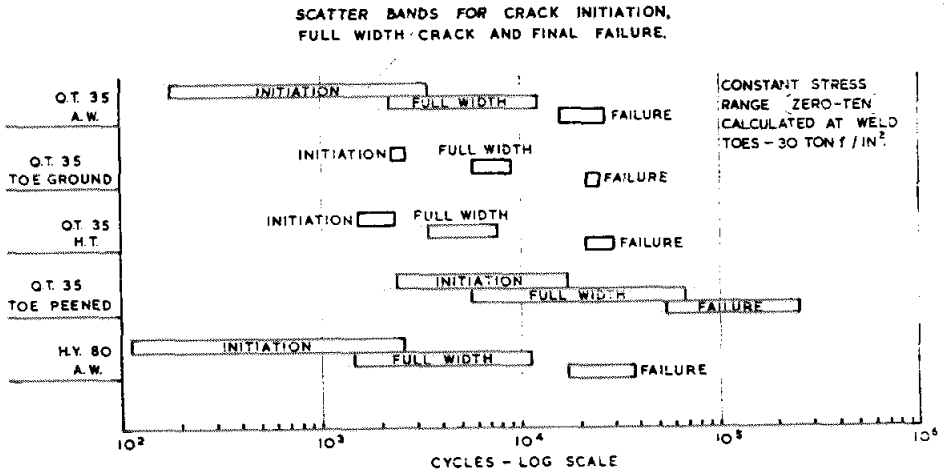


FIG. 17. Results from three-point bend fatigue tests on tee-butt welds.

significantly delays normal crack initiation and final failure. It will be noted that results from peened specimens indicate that in some cases initiation and growth to full width has taken place very early in the total life: however, these cracks would be shallow and develop slowly through material affected by peening process. It is important to ensure that the peening operation itself does not create short transverse lamellar tears or fusion line defects. In one test where lamellar tears were opened up under the tee-butt weld by excessive peening, the total fatigue life was still greater than expected for as-welded specimens. It is emphasized that these findings relating to peening apply to tee-butt welds and may not apply to other types of joint.

● INDICATES MEAN VALUE.

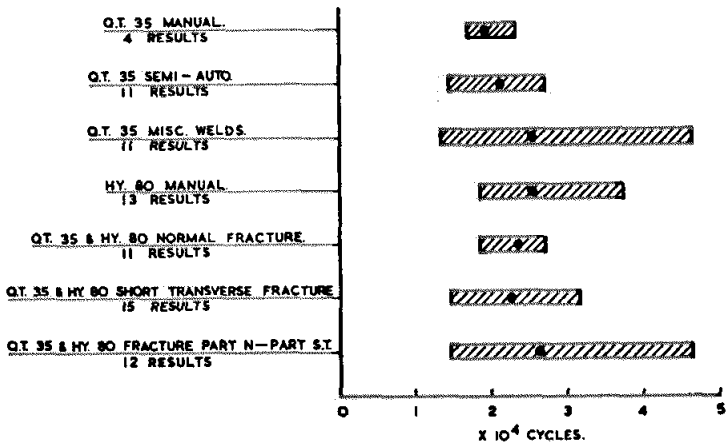


FIG. 18. Scatter bands for three-point bend fatigue tests using different steels, electrodes, welding processes and techniques and for various modes of fractures.

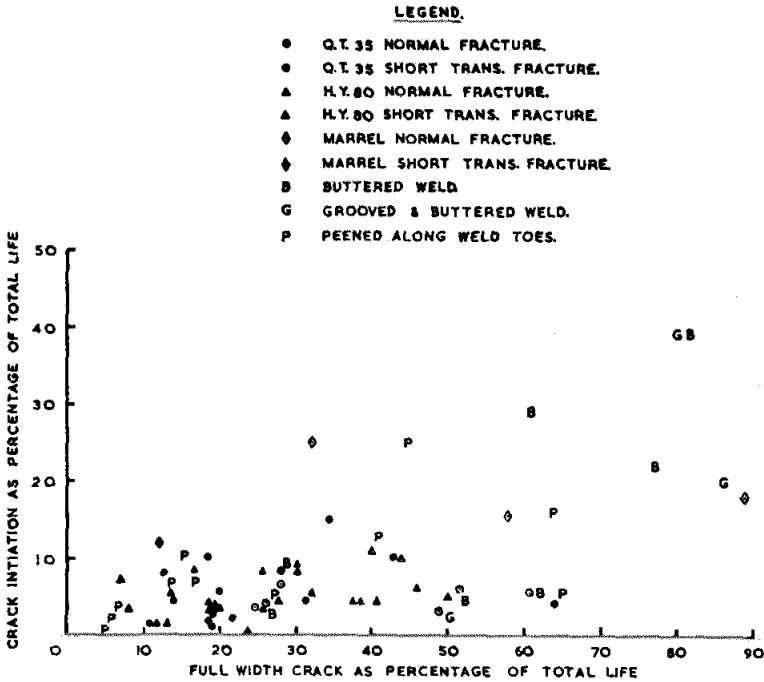


FIG. 19. Data relating fatigue crack initiation and full width crack to total life.

Rate of growth of fatigue cracks in three-point bend tests

Figure 19 shows the data obtained from three-point bend tests on Q.T.35 and H.Y.80 tee-butt welds tested at a stress range of 30tonf/in.^2 , calculated at the weld toe; cycles to crack initiation and to full width expressed as a percentage of total life. The ordinate is the percentage of total life up to first sign of initiation. The abscissa is the percentage of total life up to full width on any one side of the specimen. Most of the specimens initiated cracks at a life which was less than 10 per cent of total to failure and developed cracks to full width at a life less than 50 per cent of total to failure. This data is replotted in Fig. 20 as a histogram which indicates that crack growth to full width generally occurred at an earlier percentage of total life to failure in the case of specimens which failed in a short transverse manner. Figures 21(a) and (b) indicate typical rate of crack growth to full width of a knee-bend specimen and the rate at which area of crack grew for the specimen shown in Fig. 16.

Correlation between results from type tests and those from large structure

Some correlation between results of type tests and the onset of failure in parts of a structure has been obtained as a result of a test on a large stiffened box-shaped vessel specially made from $1\frac{1}{2}$ in.-thick Q.T.35 which was cyclically pressurized internally with sea-water and on which wire resistance strain gauges were affixed to record strain variations. Figure 22 shows how the laboratory type test results predicted the failure of the vessel at intercostal, axially loaded butt welds and tee-butt welds joining them with shell plating where stress ranges were approximately known. In this vessel half of the boundary tee-butt welds were mechanically peened and no crack could be found in them after the tests were over. The measured stresses in the vessel indicated that there had been some misalignment in construction which almost certainly shortened the fatigue life.

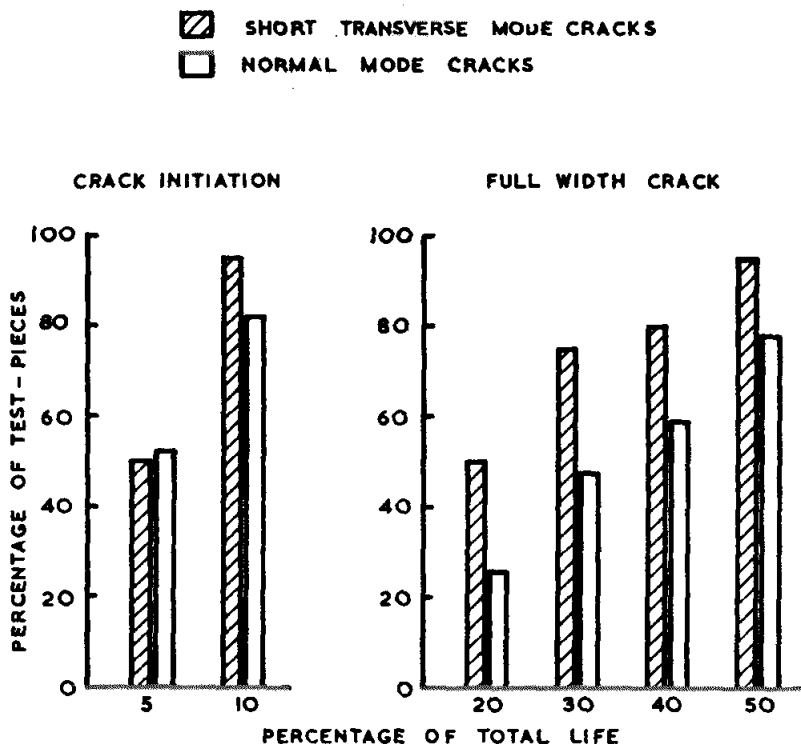


FIG. 20. Histogram showing percentage of total life at which three-point bend test pieces initiate and develop full width crack—comparing short transverse and normal fracture modes.

CONCLUSIONS

This discourse has been written with the object of underlining a number of important points relating to the fatigue strength of welded engineering structures made from structural steel. These may be summarized as follows:

(a) *Practical*

That the mode of failure in fatigue tests may be much influenced by the cleanness of steel (freedom from non-metallic inclusions) if the loading is applied normal to the plate surface.

That cracks tend to appear along the toe line of tee-butt welds very early on in the fatigue life, thereafter the rate of growth being dependent upon the loading configuration and cleanness.

That mechanical peening carefully applied affords a promising method of improving the low-cycle fatigue strength of tee-butt welded joints.

That reliable design information can only be obtained from fatigue tests on specimens which are designed and loaded so as to reasonably simulate practical cases.

There has been some success in correlating the short life fatigue performance of suitably designed uniaxially loaded type test pieces with that observed during the testing of a large box-shaped structure.

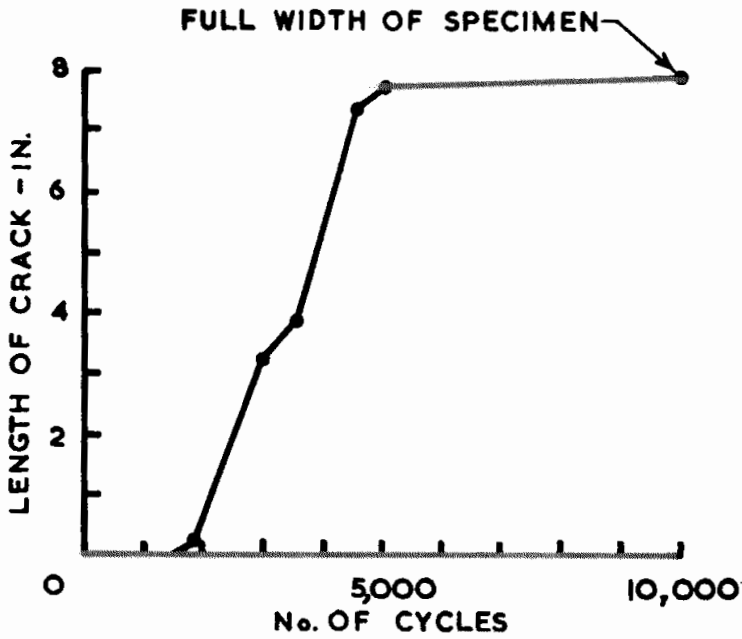


FIG. 21. (a) Plot of rate of crack growth along weld toe of knee-bend test piece.

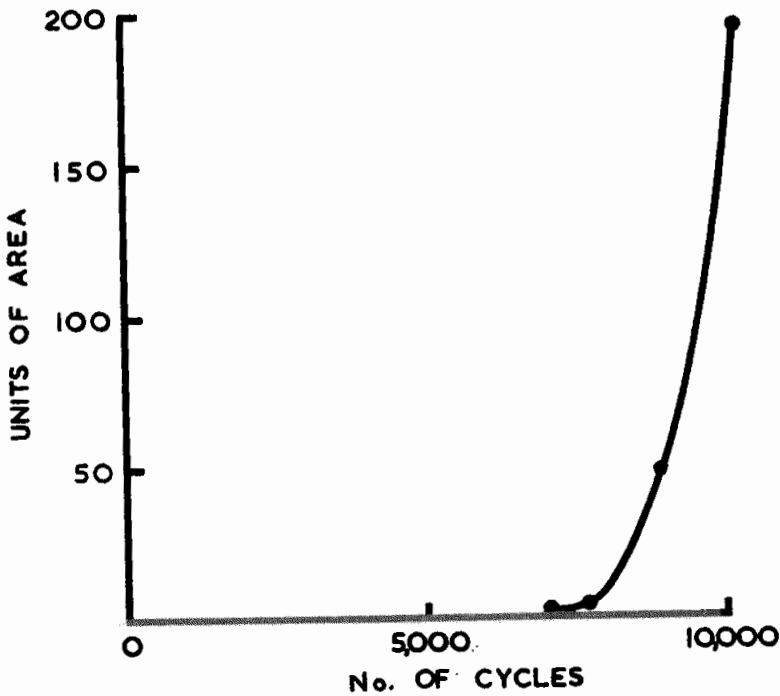


FIG. 21. (b) Rate of growth of fatigue fracture area—short transverse mode—in knee-bend test piece.

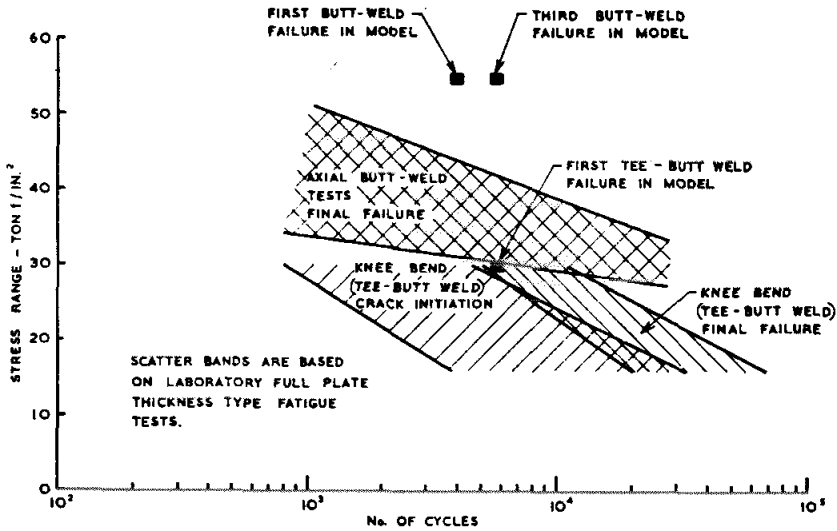


FIG. 22. Correlation between type test results and full-scale model test.

(b) *General*

That ratio of $\frac{\text{design stress}}{\text{yield stress}}$ of structural steels decreases sharply with increase in U.T.S. for a given fatigue life.

That the changes in fatigue behaviour in structural steels correlate with changes in $\frac{\text{yield}}{\text{U.T.S.}}$ ratio and uniform extension of gauge length at U.T.S. obtained from simple tensile tests.

That little advantage can be taken of higher strength steels with severe stress concentrations at long life.

That advantage can be taken of higher strength steels with stress concentrations up to an optimum U.T.S. depending upon the severity of the stress concentrations and the life to failure.

That the effective limiting fatigue stress reduction factor increases with increase in U.T.S. and increase in cyclic life.

These practical and general conclusions indicate that the fatigue life of higher strength steels may be a severe limitation unless attention is paid to matters such as cleanness of steel, fabrication details of design and methods of delaying the onset of fatigue cracks or reducing their rate of growth.

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APPENDIX

SPECIFICATION GOVERNING THE MECHANICAL TOE PEENING OF TEE-BUTT WELDS

INTRODUCTION

This specification states the requirements, type of tool and method to be used for the mechanical toe peening of tee-butt welds as a post-weld treatment applied to full penetration, tee-butt welded connections.

Region to be peened

The peening operation is to be applied to toes on both sides of the weld fillet, i.e. the weld/plate intersection. Undercut of plate to be restricted to give not more than $\frac{1}{32}$ in. undercut measured normal to plate surface, but occasional penetration up to $\frac{1}{16}$ in. will be accepted at the discretion of the Inspecting Authority.

Required shape of peened surface

The peened area to be smooth, between $\frac{3}{32}$ in. and $\frac{1}{2}$ in. radius measuring $\frac{1}{2}$ in. along a chord surface and is to be continuous along the edge of the weld.

Appearance of peened surface

Surface to be smooth, free of chatter, marks and other blemishes. Undercutting resulting from welding to be peened smooth to the satisfaction of the Inspecting Authority.

Equipment(a) *Type and shape of tool*

A chisel type of caulking tool to be ground to the form shown in Fig. 23.

(b) *Type of Hammer*

A standard pneumatic $1\frac{1}{2}$ in. diameter riveting hammer to be used.

(c) *Air Supply*

An adequate supply of air to be available at constant pressure between 85lb/in.² and 90lb/in.².

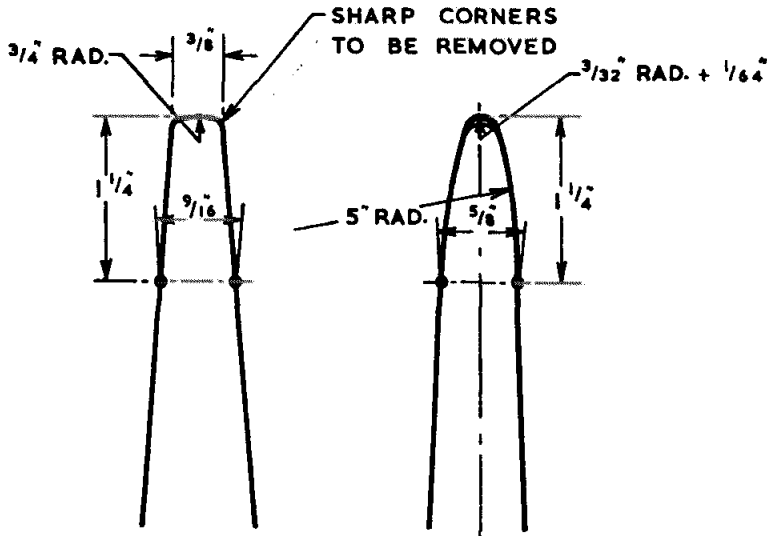


FIG. 23. N.C.R.E. tool for toe peening.

Method

(a) Handling and angle of tool

The tool to be held firmly against the weld toe at an angle between 45° and 55° to the peened plate surface. The $\frac{3}{8}$ in. width of the tool to be parallel to the weld toe.

(b) Speed of peening

Tool to be advanced at a speed of between 3ft and 4ft/min. using the hammer at full pressure.

(c) Number of runs

Peening operation to be completed in one run. If the sharp corner between weld and plate is still visible a second run may be made. No more than two runs are to be made without specific authority from the Inspecting Authority.

Inspection

(a) Visual

Visual inspection to be made for surface finish, extent of metal deformation and continuity of peening.

(b) N.D.T. Examination

100 per cent ultrasonic examination of peened welds using V.L.O. probing technique to be carried out as soon as possible after peening to search for laminar short transverse defects in the plane of the plate immediately below the weld. Any defects found are to be carefully and accurately recorded and reported.