The Influence of Screw Forming Methods on the Fatigue Strength of Large Bolts*

R. COOK, M.Sc. (Member)† and W. McCLIMONT, B.Sc. (Member)‡

Fatigue tests have been carried out to determine a reliable limiting stress range for 3-in. diameter bolts with accurately formed threads, to investigate the effect of different thread forming methods including form rolling and root rolling and to determine the effect on fatigue strength of errors in pitch of the mating threads.

Before dealing in detail with the fatigue tests, theoretical consideration is given to the relative effects of thread loading and thread form on the overall stress concentration factor, and to the effect of pitch errors or taper of the threads on the load distribution along the threads in engagement. From this a theory is formulated regarding the effects of inaccuracies in pitch on the fatigue strength or endurance. Published data on the effect of thread rolling are also surveyed.

It is shown that by careful control of machining accuracy it is possible to produce bolts having a fatigue strength within close limits of a known value. In production bolts extreme accuracy in this respect is by no means essential since it is shown that inaccuracies in pitch do not cause any reduction in fatigue strength but may, on the contrary, increase it. It is essential, however, that the form and finish of the threads should be as good as possible. Particulars are given of the accuracy of various thread forming methods, including lathe cutting, milling, grinding, form rolling and cutting on a high speed, semi-automatic lathe.

Striking improvements in fatigue strength were obtained from the form rolled and root rolled test bolts when compared with cut-thread specimens. Form rolling increased the fatigue strength of bolts made from forgings some 2¼ to 3 times and the rolling of the thread roots gave almost as great an increase. These increases are greater than any indicated by previously published results, but have been confirmed by tests with mild steels of three different compositions.

INTRODUCTION

The results of a systematic series of fatigue tests of large bolts were presented to this Institute in 1952 by Mr Bryan Taylor(1). These results had been obtained as part of an investigation being undertaken by the British Shipbuilding Research Association into the factors influencing the strength of bolts of the type used in marine engines when subjected to repeated stresses. The threads of all the bolts tested had been lathe-cut, using a single point tool, and finished with a ground thread chaser. This practice had been adopted because, although when testing screwed components in fatigue it is usual to specify ground threads of the greatest accuracy to reduce as far as possible scatter of the test points, the object had been to obtain results which could be applied directly to marine engine design problems.

Taylor presented the results of his tests on twenty-four 3-in. diameter bolts on semi-logarithmic co-ordinates and his S-N diagram is reproduced here as Fig. 1. He attributed the wide scatter of the results to errors in pitch and form of the mating threads and, of those, he considered that pitch errors were the predominating influence. From examination of the details of each of his twenty-four test assemblies, he suggested that bolts and nuts with accurately formed threads would give results falling within the narrower scatter band indicated by the shaded area in Fig. 1. Depending on whether pitch errors produced a more, or less, favourable stress distribution in the bolt than would be obtained with accurate threads, the fatigue strength would be increased or decreased respectively beyond the limits of this narrow band.

It was apparent that, in order to provide reliable data for design purposes, further tests would be necessary, firstly to

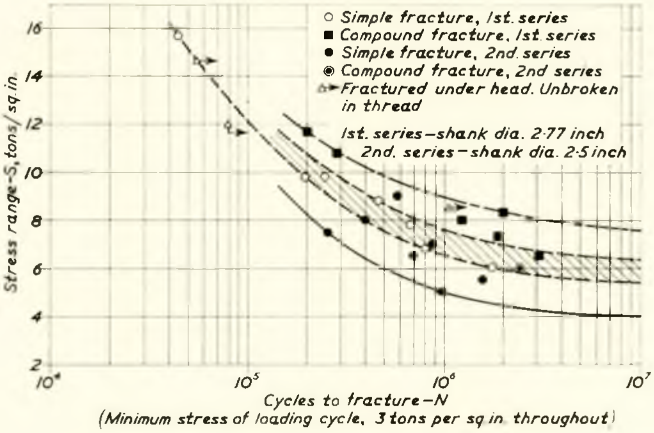


FIG. 1—*S-N diagram for 3-in. bolts (Taylor 1952)*

---

* This paper was circulated for written discussion.

† Marine Engineer, British Shipbuilding Research Association.

‡ Principal Assistant Marine Engineer, British Shipbuilding Research Association.

establish a reliable limiting stress range* for bolts with accurately formed threads, and secondly to investigate the influence of the accuracy of thread production. The results of these B.S.R.A. tests are given in the present paper.

Various ways have been suggested of increasing the fatigue strength of bolt and nut assemblies, including surface treatments such as nitriding, cyaniding, carburizing and rolling, the use of taper or differential-pitch threads, nut materials with a lower elastic modulus than the bolt, and modified nut designs. Of these different methods, thread rolling seemed to offer several advantages for use in the marine engineering industry. It is a cheap and rapid process, which can produce extremely accurate results, with the threads formed entirely by cold rolling from cylindrical blanks.

The form rolling process can only be carried out in a machine designed for the purpose, and a set of dies is required for each size of thread produced. An alternative method is to roll only the roots of the threads after normal screw cutting. Although this process does not offer the advantages of speed and accuracy of form rolling, only a simple attachment is required which can be made up in any engineering shop and can be used in the lathe as a finishing process after screw cutting.

1) *Theoretical Considerations of Thread Pitch Accuracy*

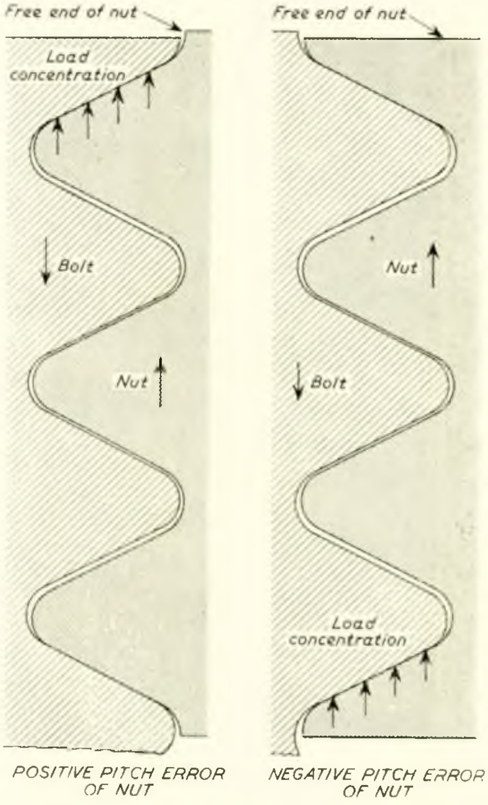
Stress Concentrations in the Bolt

The load distribution along a screw thread engaging with a nut of the normal type is far from uniform, with a high concentration of stress at the root of the first thread engaging with the nut. The overall stress concentration factor (s.c.f.), by which the nominal axial core stress is multiplied to give the maximum stress at the roots of the threads is composed of two elements, namely, that due to the notch effect of the thread form (form s.c.f.) and that due to the thread loading (loading s.c.f.). For any given thread form, the form s.c.f. depends theoretically only on the pitch to diameter ratio of the bolt threads, although the actual strength reduction factor† may be affected by inaccuracies in thread form and poor finish as well as by the size of the bolt and the properties of the material used. The form s.c.f. has a constant value along the threads; for the larger bolts which are considered in this paper (3-in. diameter 6 t.p.i. Whitworth form threads) the theoretical form s.c.f. has a value of 3·5. Unlike the form s.c.f., the theoretical loading s.c.f. varies along the threads in engagement from a minimum value at the free face of the nut to a maximum at the bearing face of the nut. The maximum value depends on the pitch, form and diameter of the bolt threads and also on the proportions of the nut and the coefficient of friction‡ between the mating threads. For the 3-in. test bolts, the maximum loading s.c.f. for accurately formed threads of uniform pitch and diameter has been calculated to have a value of 4·7 and this result indicates that the stress induced at the thread root by the load applied to the thread projection has a greater effect in reducing the strength of the bolt under fatigue loading than the notch effect of the threads themselves. In these s.c.f. calculations the work of Neuber(2), Heywood(3) and Sopwith(4) has been used.

The stress concentration effects due to thread form and loading are additive but as the positions of maximum stress caused by the two separate factors are not coincident in the thread root an expression obtained by Heywood(3) has been used to obtain a corrected overall stress concentration factor of 6·8. Since, however, the foregoing analysis is based on the assumption that the material behaves elastically, it might be expected that the strength reduction factor would be somewhat lower than the overall stress concentration factor. This follows from the fact that, particularly in mild steel components, local yielding leads to a diminution of the stress peak and some redistribution of the load. On the other hand there is some evidence(5) that in large parts the strength reduction factor approaches the theoretical value even in mild steel; this is supported by the results of the present investigation which are discussed later.

Load Distribution along the Nut

In the above analysis it is assumed, of course, that the nut and bolt threads are of uniform pitch and perfectly formed. However, unless the threads are produced with the greatest precision the maximum stress concentration is likely to vary considerably both in magnitude and position along the thread. This point is illustrated in Fig. 2, from which it will be seen that a positive pitch error of the nut or negative pitch error of the bolt threads* has the beneficial effect of removing the point of load concentration from the loaded face of the nut.



POSITIVE PITCH ERROR OF NUT NEGATIVE PITCH ERROR OF NUT

FIG. 2—*Effect of pitch error in mating threads*

It is virtually impossible to calculate the stress distribution along the bolt threads when pitch errors are present if yielding of the threads is to be taken into account. However, drawing on the work of Stoeckly and Macke(6), the curves shown in Fig. 3 are put forward as representing a reasonable picture of the variation of the maximum stress at the thread roots along the length of the thread for different degrees of pitch error. With yielding of the threads the maximum thread root stress can in no case exceed the yield stress and there is therefore, a horizontal cut-off of the curves in Fig. 3. It has been assumed that the yield stress has a constant value,

---

* The term "limiting stress range" is used throughout this paper to denote the maximum range of fluctuating tensile stress that can be applied for an indefinite number of cycles without failure, where the mean stress of the loading cycle is not zero. The deleterious effects of corrosion on the fatigue strength are not considered; under such conditions the limiting stress range is likely to be greatly reduced.

† The strength reduction factor is given by the ratio:

$$\frac{\textit{fatigue strength of unnotched specimen}}{\textit{fatigue strength of actual component}}$$

This factor depends on the size of the component tested and the notch sensitivity of the material; for axial loading the size of the unnotched specimen is immaterial.

‡ Assumed for purposes of calculation to have a value of 0·2.

* For brevity this is referred to later as a positive pitch error. The opposite condition of a negative pitch error of the nut threads (a shortening of pitch) or a positive pitch error in the bolt threads is termed a negative pitch error.

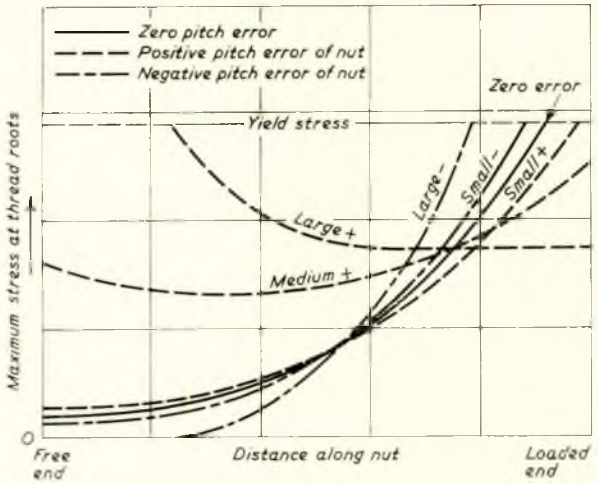


FIG. 3—*Probable stress distribution along bolt threads showing the effect of positive and negative pitch errors in the nut*

the effect of strain hardening being neglected owing to the small amount of yielding that occurs.

Effect of Pitch Errors on Fatigue Strength

In bolts that fail in service and also in bolts tested under controlled conditions, fatigue cracks start not only at the first thread of the bolt engaging with the nut but sometimes are found to start at other positions along the thread within the nut. Using the curves shown in Fig. 3 as a basis, a hypothesis can be built up to account for this behaviour.

For zero pitch error the maximum concentration of stress in the bolt occurs at the point along the thread in line with the loaded face of the nut. If the stress range is sufficiently high not only will a simple fracture* commence at this point of greatest stress concentration but a certain amount of local yielding will also take place. With a small positive pitch error in the nut the extent of yielding at the loaded face is decreased slightly and there is no change either in the mode of failure or in the fatigue strength. A medium positive pitch error, however, eliminates all yield, reduces the loading s.c.f., and consequently results in an increase in fatigue strength. Yield at the free end of the nut is caused by a large positive pitch error, the greater the error the greater being the zone of yielding. Under such conditions the maximum concentration of stress is in the yield zone at the free end and a fatigue crack is likely to start at some point in this zone. The occurrence of a crack will cause a transference of load from the free end of the nut to a region nearer the loaded face, thus reducing the load at the fractured section. This will slow down and may even stop the progress of the crack but the yield zone will be extended further causing another crack to start. This will in turn cause the cycle to be repeated and so the cycle will go on until complete failure occurs at or near the loaded end of the nut. The final result is a compound fracture having many starts and the bolt has a much increased endurance compared with one which has failed by simple fracture.

Turning now to pitch errors in the opposite direction, it will be seen from Fig. 3 that a small negative pitch error in the nut will cause a slight increase in the zone of yield at the loaded end and it is considered that this will again result in a simple fracture somewhere in the yield zone, probably still at the first thread. An increase in the negative pitch error will lead merely to a further extension of the yield zone. With a large negative pitch error a simple fracture is most likely to occur, but it is possible for a crack to start at the inner part of the yield zone, in which case load transference could again take place resulting in a compound fracture. Such a compound fracture would have fewer starts than in the case of the positive pitch error but a large negative pitch error may possibly give a somewhat increased bolt endurance compared with that of an accurately machined bolt. It follows therefore, that negative pitch errors in the nut will not reduce the fatigue strength below that for perfect threads, provided that the overall stress concentration factor for zero pitch error is sufficiently high to produce yielding of the threads at the loaded end.

Although the foregoing hypothesis is based on the assumption that pitch errors are of a uniform nature, it could be extended to include random errors which would have the same cumulative effect as uniform errors in pitch.

To sum up, it is postulated that pitch errors of the bolt or nut, either negative or positive, do not lead to any lowering of the fatigue strength of a bolt. In other words, the limiting stress range obtained from bolts with accurately produced threads represents the minimum fatigue strength for the size of bolt tested, provided that the thread form and surface finish do not depart from reasonably high standards. The fatigue strength may, however, be raised by positive pitch errors.

2) *Published Data on the Effect of Thread Rolling*

The results of previous investigations have, in general, indicated that cold-working of the surface increases the resistance to fatigue but some materials respond to the treatment more favourably than others. From a study of the results(7) (8) (9) and (10) of fatigue tests on bolts under axial loading by a number of different investigators, several points of interest emerge. Specimens made from a dead-soft mild steel were unaffected by either form rolling or after-rolling; such material, however, would not normally be used for important dynamically loaded bolts. Form rolled specimens from a medium carbon steel showed a substantial increase in fatigue strength which tends to support the theory that a high ratio of yield stress to ultimate stress is essential for a material to be improved by rolling. At the same time tests should be noted in which it was shown that form rolling may reduce the fatigue strength of bolts made from high-tensile alloy steels with yield points approaching the ultimate strength.

The tests on 1-in. Whitworth bolts by Dinner and Felix at Sulzer Bros., Winterthur, gave favourable results from form rolling using a steel of similar composition to that used for all the B.S.R.A. work on bolts up to this point. It is interesting to note that the mechanical properties of these materials did not differ very greatly from those of the dead-soft mild steel mentioned earlier which was unaffected by the rolling process.

The foregoing results on which comment has been made do not by any means form a comprehensive list of all the published work on the subject; having regard to all the previous work it appeared that the fatigue strength of plain carbon-steel bolts was likely to be increased both by form rolling of the threads and by rolling of the thread roots after cutting. The available data were, however, inadequate to allow an estimate to be made of the increase likely to result and much of the previous work introduced the possibility of a size effect when considering the bolts used in the running gear of slow speed marine engines. It was decided, therefore, to carry out fatigue tests on 3-in. and 1-in. diameter bolts form rolled in the same material as had been used up to that time in the B.S.R.A. bolt tests.

The material properties required to give the best results were obscure but it was evident that the composition of the steel was of importance. It was suspected that the manganese-carbon ratio probably had a significant influence. Accordingly a further investigation was made using two mild steels of different manganese and carbon contents. The results obtained with all three steels are included in the paper.

At the same time fatigue tests were carried out on 1-in. diameter bolts of each of the same three steels with lathe-cut or milled threads finished by after-rolling.

In the form rolling process, the extent of plastic deformation is governed by the pitch and form of the threads pro-

---

* A simple fracture is one in which the fatigue crack starts from a single point and progresses across the section until failure in tension ultimately occurs. In compound fractures cracks commence from a number of different points.

Table I.—Analyses of materials used.

	Steel used for bolts, 1st composition	Steel used for bolts, 2nd composition	Steel used for bolts, 3rd composition	Steel used for nuts, with bolts of 1st composition	Steel used for nuts, with bolts of 2nd composition
Carbon	0·16	0·15	0·21	0·115	0·12 approximately
Manganese	1·0	0·55	0·65	0·51	0·5 approximately
Silicon	0·18	0·15 maximum	0·07	0·18	0·06
Sulphur	0·043	0·04 maximum	0·045	0·029	0·029
Phosphorus	0·049	0·04 maximum	0·030	0·021	0·024

duced, the diameter of the blank being chosen so that the metal displaced is just sufficient to fill the dies. When rolling the thread roots after cutting, however, the deformation depends not only on the properties of the material but on the roller shape, the pressure applied, and the number of passes given. From a survey of the literature, no hard and fast rule could be produced on the amount of rolling required although all previous workers were agreed that to be effective the rolling process must produce visual evidence of plastic deformation at the thread roots. In the tests with the first material a roller pressure was chosen which just produced visual evidence of deformation; during the later tests the opportunity was taken to determine the effect of the degree of rolling.

3) *Fatigue Tests*

Material and Manufacture of Specimens

Details are given in Table I of the analysis of the materials used for the bolts and nuts. The first composition was used for all the tests on the effects of thread accuracy.

All the test bolts were machined from forgings; 6½-in. square for the 3-in. bolts and 5½-in. square for the 1-in. bolts. All forgings were given a normalizing and tempering heat treatment which was varied in accordance with the size. Details of the mechanical properties of the materials used for the bolts are given in Table II. The nuts used with series 1, 2 and 3 had tensile strength 28·2 tons/sq. in. and elongation 38 per cent; for series 4 the corresponding values were 26·0 and 35; for series 5, 6 and 7 these values were 27·2 and 40. The tensile strength of the nuts used with the remaining series was 25 to 27 tons/sq. in.

Details of the 3-in. diameter test bolts for series 1, 2 and 3 are given in Table III(a). The bolts for series 4 were identical at the screwed end and in overall length but to reduce the stress concentration at the junction of the fillet under the head with the shank a much more generous fillet radius was provided and the surface was improved by emery polishing; this procedure was again adopted for series 8 and 9 and details of these bolts are shown in Table III(b).

The 1-in. diameter test bolts for series 5 are shown in Table III(c) and again it was necessary to provide a more generous fillet radius under the head for series 7 to 15 as shown in Table III(d). To obtain a similar stengthening under the head for the form rolled bolts in series 6 the design shown in Fig. 4 was adopted.

The bolts of series 1 had threads cut on a high speed semi-automatic lathe employing a single-point cutting tool.

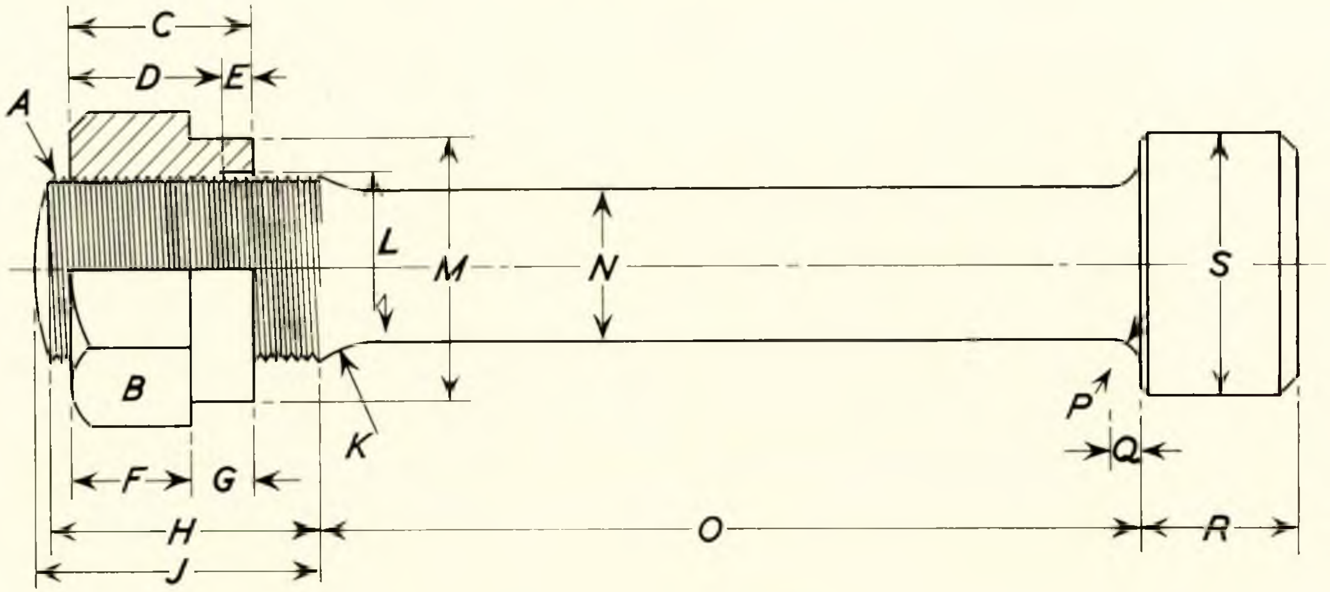
The form rolling of the threads of series 4, 6, 9 and 11 was carried out on a Steinle No. 2 centreless thread generator. This machine in its standard form is capable of rolling threads from ⅜-in. to 3-in. diameter.

In form rolling, the threads are formed from a cylindrical blank which in the majority of cases is carried on a rest, similar to that used in a centreless grinding machine, positioned

Table II—Mechanical properties of materials

Series No.	Method of thread production	Tensile strength tons/sq. in.	Yield strength, tons/sq. in.	Elongation, per cent.	Izod value ft. lb.	Average Brinell hardness number
		First composition				
1. (3-in.)	High speed, semi-automatic lathe	30·8 to 32·2	17·6	35	66 to 98	142
2. (3-in.)	Ground	33·2 to 34·0	17·6	34 to 36	71 to 82	145
3. (3-in.)	Milled	33·2	17·6	36	71 to 82	153
4. (3-in.)	Form rolled	34·0	17·6	34	72 to 79	165
5. (1-in.)	Lathe cut	30·8	18·5	38	97 to 101	155
6. (1-in.)	Form rolled	30·8	18·5	38	97 to 101	155
7. (1-in.)	Lathe cut and root rolled (350 lb. roller load)	30·8	18·5	35	71 to 91	152
		Second composition				
8. (3-in.)	Milled	26·24	16·0	42·8	55·5 to 60	
9. (3-in.)	Form rolled	26·24	16·0	42·8	55·5 to 60	
10. (1-in.)	Milled	25·03	14·32	45	76·5 to 78	
11. (1-in.)	Form rolled	25·03	14·32	45	76·5 to 78	
12. (1-in.)	Milled and root rolled (350 lb. roller load)	25·03	14·32	45	76·5 to 78	
13. (1-in.)	Milled and root rolled (250 lb. roller load)	25·03	14·32	45	76·5 to 78	
		Third composition				
14. (1-in.)	Milled	31·0	21·0	38·5		
15. (1-in.)	Milled and root rolled (350 lb. roller load)	31·0	21·0	38·5		

Table III—Details of test bolts.



	A	*B*	*C*	*D*	*E*	*F*	*G*	*H*	*J*	*K*	*L*	*M*	*N*	*O*	*P*	*Q*	*R*	*S*
(*a*) 3-in. test bolts (Series 1-3)	Screwed 3-in. diameter Whitworth form. 6 T.P.I.	4·53 across flats	3	2·5	0·5	2	1·0	4·5	–	1 radius	–	4·29 diameter	2·5 diameter	13·5	0·375 radius	–	2·6	4·29 diameter
(*b*) 3-in. test bolts (series 4, 8 and 9)	Screwed 3-in. diameter Whitworth form. 6 T.P.I.	4·53 across flats	3	2·5	0·5	2	1·0	4·5	–	1 radius	–	4·29 diameter	2·5 diameter	13·94	1 radius	0·81	2·10	4·29 diameter
(*c*) 1-in. test bolts (Series 5)	Screwed 1-in. diameter Whitworth form 8 T.P.I.	1·5 across flats	1·125	0·845	0·28	0·78	0·345	–	1·5	0·33 radius	1·03 diameter	1·430 diameter	0·830 diameter	4·5	0·125 radius	–	0·875	1·430 diameter
(*d*) 1-in. test bolts (Series 7-15)	Screwed 1-in. diameter Whitworth form 8 T.P.I.	1·5 across flats	1·125	0·845	0·28	0·78	0·345	–	1·5	0·33 radius	1·03 diameter	1·430 diameter	0·830 diameter	4·25	0·33 radius	–	0·75	1·430 diameter

All dimensions in inches.

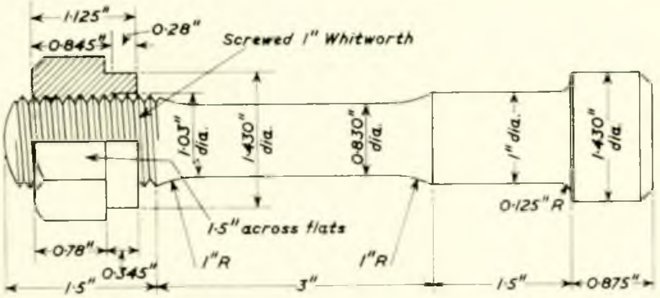


FIG. 4—*Details of 1-in. test bolts (series 6)*

between two forming rolls. For heavy work, however, a fixture is used to carry the bolt between centres. This fixture slides between the rolls to locate the length of thread to be rolled, and allows the finished work to be withdrawn for removal from the machine. One of the rolls revolves about a stationary axis while the other, which is carried by an hydraulically operated slide, is fed inwards to apply the pressure necessary for the threading operation. No metal is removed in the process, the thread grooves being formed by displacement, and consequently an accurately turned blank with a fairly high quality surface finish is required for components to close tolerances. The diameter of the blank is approximately equal to the effective diameter of the finished thread. For producing right-hand threads, both rolls are threaded left-hand with multi-start threads of the required helix angle and thread form for the work to be carried out. Each set of dies is therefore suitable only for producing threads of one diameter and pitch. No longitudinal movement of the workpiece takes place during rolling, the blank merely revolving in contact with the threading rolls until the full depth of thread is generated. On completion, the moving roll returns to its starting position and the bolt may then be removed.

The time required for forming the threads is very much less than that taken by any other method. For the 3-in. bolts, the thread rolling operation took only one minute at a roll speed of 75 r.p.m. Comparing the thread forming times for each bolt of a batch of, say, twenty, including the times required for setting-up in the machines and adjustment would give figures of the following order:

Lathe-cut	60 minutes
High speed semi-automatic lathe	25 minutes
Ground	105 minutes
Milled	95 minutes
Form rolled	5 minutes

Details of the thread-root rolling tool used with the 1-in. bolts are shown in Fig. 5. This device was made to details kindly supplied by Dr. Horger, of the Timken Roller Bearing Co., Canton, U.S.A. It should be noted that each of the three hard-steel rollers is free to rotate and is located axially by thin washers with a small clearance, so that each roller is in advance of the previous one by one-third of a pitch. The roller-edge radii were accurately ground to a radius of 0·020in., which is 0·003in. greater than the standard root radius of a 1-in. Whitworth thread. The included angle of the roller flanks was made 30 degrees so that only the root of the thread would be in contact with the rolls.

For the after-rolling of the threads of the 1-in. test bolts of all three compositions a load at the roller of 350lb. was chosen after some preliminary tests which showed that this

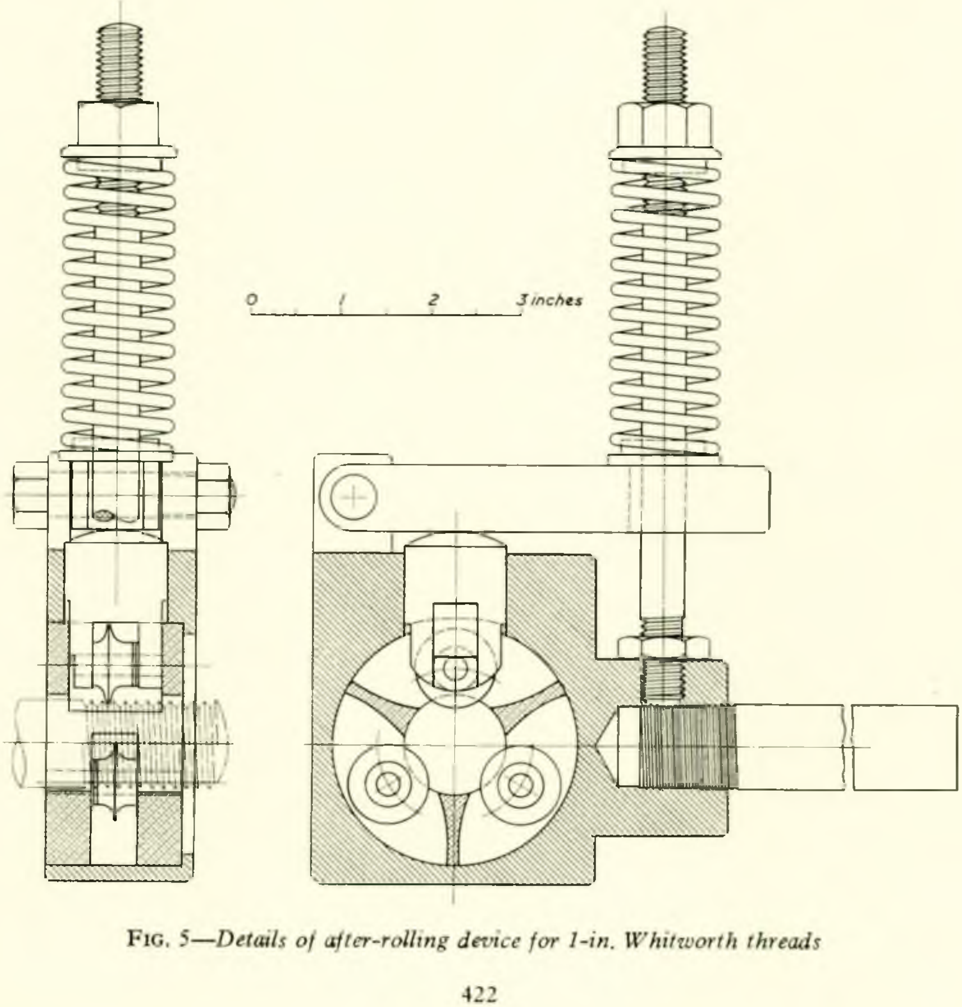


FIG. 5—*Details of after-rolling device for 1-in. Whitworth threads*

was the mean of the loads at which visual evidence of deformation of the thread roots was first obtained. For the second composition a series was also done using 250lb. roller load. In addition, to obtain further information on the optimum roller load for the second composition, a number of the 1-in. milled bolts were root rolled at different roller loads and tested at a constant stress range.

The procedure adopted at first for the after-rolling was to engage the rollers with the free end of the thread, to screw down the spring to the required compression, and then to feed the rolling attachment along the thread, holding it by hand while the bolt was turned at slow speed in the lathe. On reaching the end of the thread the rotation of the chuck was reversed, so that each thread was rolled a second time. Later it was found that the operation could be done equally well by hand with the specimen held in a vice. The resultant deformation is illustrated in Fig. 6, which shows an enlarged section of a typical thread profile of one of the test bolts of the second composition after rolling. From this it will be seen that the deformation extended over the area of maximum stress concentration where a fatigue crack normally starts.

It was found that when the threads were made to B.S. "close-fit" limits before root rolling, after rolling the threads had to be chased to relieve diametral and pitch tightness.

The threads of the 3-in. nuts were all milled, this method being adopted in preference to screw cutting in the lathe because of the greater accuracy obtainable. Two methods of cutting the threads of the 1-in. nuts were used. All the nuts used with series 5, 6 and 7 were roughed out in the lathe to a few thousandths of an inch below size and then finished by means of a ground-thread tap; the remainder of the 1-in. nuts were milled.

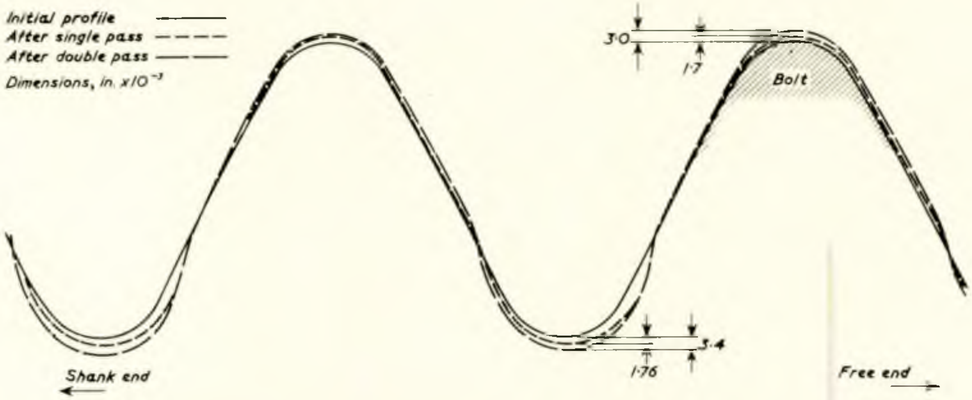


FIG. 6—*Typical thread profile after root rolling with 350lb. roller load (series 12)*

In order to investigate the effect of known pitch errors for which a hypothesis has been put forward earlier in the paper, two of the milled-thread bolts from series 3 were tested with nuts having tapered threads. A diametral taper on a nut has the same effect as a difference in pitch; for the Whitworth thread form the equivalent pitch error produced is 0·260 times the diametral taper. The bolts had been measured so that the limits of accuracy of the threads were known and great care was taken in the manufacture of the nuts by a firm of gauge and tool makers. Both nuts, which were checked for accuracy after machining, were made with a taper of 0·006in. per inch length on the diameter which was equivalent to a pitch error of 0·00156in. per inch. This value was chosen as representing a reasonable maximum error for normal machining methods. One of the nuts had the smaller diameter at the loaded end, corresponding to a negative pitch error (the "worsened" nut) and the other had the taper in the opposite direction, giving the same effect as a positive pitch error (the "improved" nut).

Accuracy of Screw Threads

Using optical projecting for examination of the thread forms, it was found that the divergence from the standard form of the bolt threads was negligible. The ground threads were formed with great precision and extremely accurate thread forms and a high quality surface finish were produced by thread rolling. The errors produced by the high-speed semi-automatic lathe and by milling occurred only at the crests and roots of the threads. In general, the finish of the threads of all the specimens was superior to that of the bolts with lathe-cut threads to which the results in Fig. 1 refer. The thread profiles produced by after-rolling have been discussed earlier and are illustrated in Fig. 6.

For the most part the effective diameters of the bolts fall within the close fit limits of British Standard 84 : 1940. The effective diameter of any bolt varied along its length due to "out-of-roundness", variations in thread form and taper of the threads. Most of the variation in those bolts that showed the greatest differences was due to taper, but the results were by no means consistent. Taper of the thread has an effect similar to an error in pitch on the distribution of load along the nut but it is considered unlikely that the maximum taper measured, which was of the order of 0·0025in. per inch(equivalent to a pitch error of approximately 0·0006in. per inch) would have any significant effect on the load distribution. It should be noted that the "improved" and "worsened" nuts had a taper equivalent to a pitch error of 0·006 in. per inch.

In checking the accuracy of pitch of the threads, the procedure recommended by N.P.L.(11) was used, i.e. errors were measured at intervals of whole pitches along four lines spaced equally around the circumference and parallel to the axis of the thread; the mean values were then obtained from the four sets of readings from each bolt. The effect of errors in pitch depends not so much on the individual errors in spacing of the adjacent turns of thread as on the additive effect of these errors, which is known as the cumulative error. To compare the accuracy of the threads a convenient yardstick is the maximum cumulative error in pitch within the length of engagement of the thread within the nut. For the bolts used in the present investigation the following values for maximum cumulative pitch error were obtained.

Series	1	High speed semi-automatic lathe	−0·0005in. per inch*
Series	2	Ground	−0·0002in. per inch
Series	3	Milled	+0·0005in. per inch
Series	4	Form rolled	−0·0005in. per inch
Series	5	Lathe-cut	−0·0012in. per inch
Series	6	Form rolled	−0·0006in. per inch
Series	7	Lathe-cut and root rolled	−0·0004in. per inch
Series	10	Milled	+0·0006in. per inch
Series	12	Milled and root rolled	+0·0020in. per inch

It was found consistently that the effect of root rolling

---

* Whilst these were the maximum errors for this series it was later found that consistent results cannot be guaranteed with this type of machine; reference is made to this again later.

was to introduce an increase of pitch of the bolt particularly at the ends of thread where the movement is less restricted.

Test Procedure

The machines used for testing the bolts were described by Taylor(1) in his paper of 1952. The 3-in. bolts were tested in a Losenhausen hydraulic pulsator with a load range of 100 tons, the speed of operation being 266 cycles per minute while the 1-in. bolts were tested in a Schenk pulsator with a load range of 20 tons at a frequency of about 2,600 cycles per minute. Particular care was taken to minimize extraneous bending stresses in the specimens by the use of spherical seatings and careful setting-up in the machines. It is extremely difficult to ensure perfect axial loading, however, and in all cases there was a small superimposed bending stress; on no occasion did this exceed 6 per cent of the direct stress and in most of the tests it was kept down to less than 3·5 per cent.

The minimum stress* of the loading cycle was maintained constant at 3 tons/sq. in. This minimum value of the loading cycle was chosen to represent the lowest probable pre-stress obtaining under normal operating conditions. The normal "loading-down" procedure was adopted, i.e. the first specimen was tested at a relatively high stress range and subsequent specimens at successively lower stress ranges, until a specimen remained unbroken after enduring 10^7 cycles (for the 3-in. specimens) or 10^8 cycles (for the 1-in. specimens) at which the fatigue curves tend to become asymptotic.

The 1-in. milled bolts of the second composition which were root rolled at various roller pressures to obtain information on the optimum roller load were all tested at a stress range 3-16 tons/sq. in.

For the 3-in. milled bolts of series 3 which were tested with the tapered-thread nuts, the applied stress range in both tests was 3-10 tons/sq. in.

Results

The results of the first three series of tests are shown plotted on semi-logarithmic co-ordinates in Fig. 7. The great majority of these bolts failed by simple fracture; there were no examples of compound fractures in which widely separated cracks were formed although in a few cases two or more cracks had evidently been initiated almost simultaneously and merged into one as they extended across the core of the bolt. In all specimens where one crack had led to failure the fracture originated at a point at the thread root between ½ and 1¼ turns from the start of the thread in the nut. Where the crack had more than one origin it was found that the nuclei were spaced not more than about ¾ of a turn of the thread apart; that farthest from the face of the nut was approximately 1¾ turns from the start of the thread.

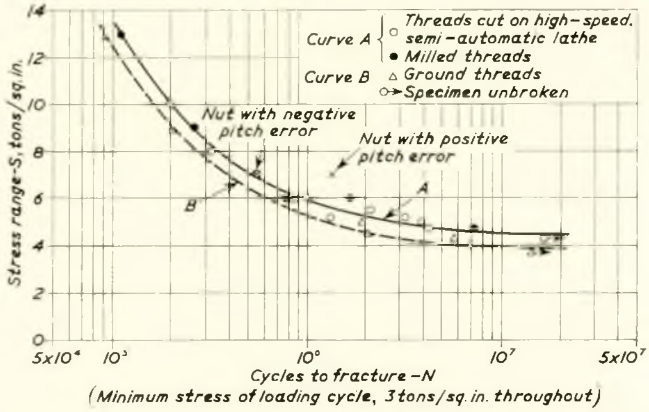


FIG. 7—*S-N diagram for 3in. bolts (series 1, 2 and 3)*

The results from the two bolts tested in conjunction with the tapered-thread nuts are plotted in Fig. 7 from which it will be seen that the improved nut (positive pitch error) increased the endurance of the bolt by 160 per cent compared with that given by the S-N curve for cut and milled threads (curve A). The worsened nut on the other hand, gave a result that fell almost exactly on this curve. It will be shown later that curve A represents the S-N curve for accurately machined threads: both results are therefore in agreement with the hypothesis put forward earlier regarding the effect of pitch errors.

The results of series 3, 4, 8 and 9 are shown plotted on semi-logarithmic co-ordinates in Fig. 8, giving a comparison between milling and form rolling for 3-in. diameter bolts. It will be seen that, owing to the failure of the first two form rolled specimens (series 4) at the fillet under the head, only four test points were obtained to construct the S-N curve. Failure under the head of later specimens was prevented by the introduction of an easier fillet at this section, as mentioned earlier. Although the number of test points is insufficient to allow an accurate determination of the limiting stress range, it is considered that a reasonable indication has been obtained. There is no reason to doubt the reliability of the results plotted, as the three fractures obtained were all of the simple type.

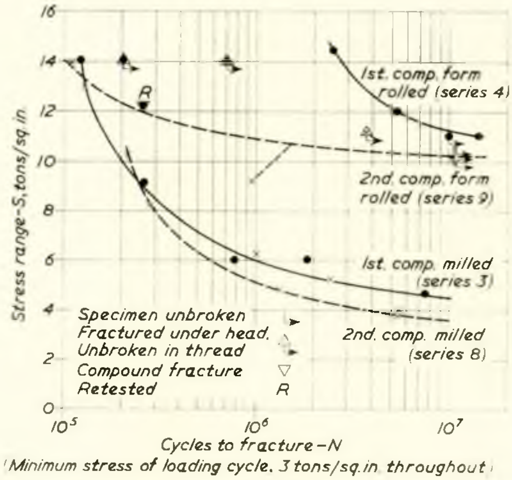


FIG. 8—*S-N curves for 3in. diameter bolts comparing milling and form rolling on two mild steels*

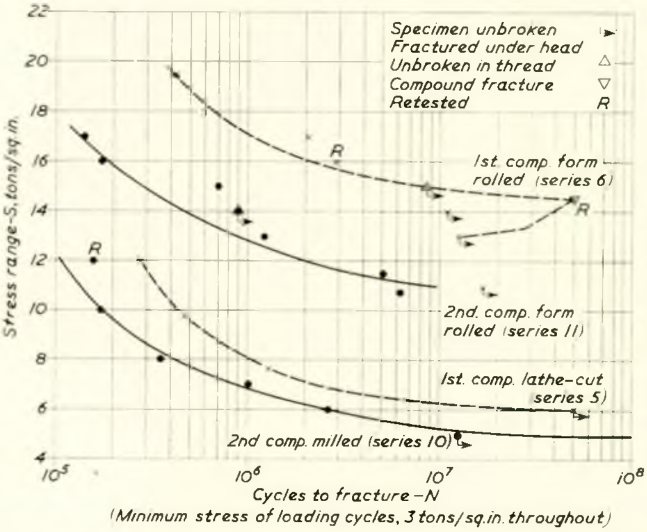


FIG. 9—*S-N curves for 1in. diameter bolts comparing milling and form rolling on two mild steels*

---

*The stresses quoted in this paper refer to the mean stress calculated on the area at the root of the threads.

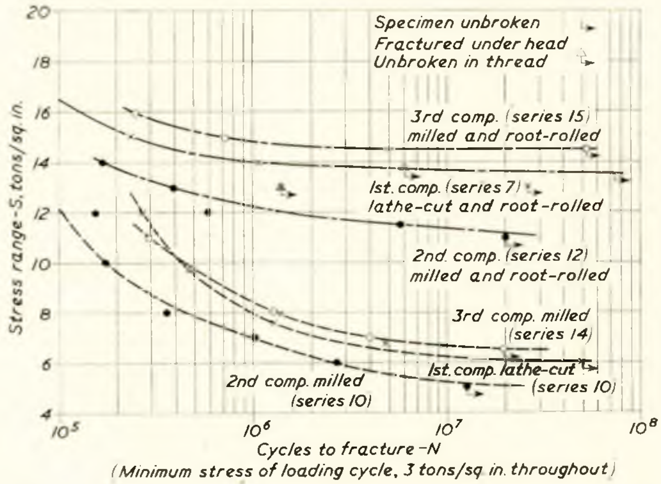


FIG. 10—*S-N curves for 1in. diameter bolts showing effect of root rolling on three mild steels (350lb. roller load)*

The third bolt tested of series 4 remained unbroken after being subjected to 10 million cycles at a stress range of 11 tons/sq. in.; this endurance was extraordinary when compared with the results obtained up to that point in the investigation. As it was thought that this might have arisen from cracks in the bolt in the section within the nut, with consequent re-distribution of load, as discussed earlier in this paper, the assembly was sectioned for examination. A most unusual feature was revealed by this examination: no fatigue cracks had been formed in the bolt but several were found in the nut threads. One of these had completely fractured the first thread in the nut, and a second crack had extended a considerable distance from the root of the second thread. A third crack had started at a position about half-way along the threads, which can be attributed to a local inaccuracy in pitch of the mating threads.

Of the 14 specimens of the second composition tested in the 3-in. size (series 8 and 9), 11 were simple fractures at the first thread in the nut, 1 failed at the radius under the head, 1 remained unbroken and 1 was a compound fracture. The compound fracture was obtained at a high stress range on a specimen which had already been submitted to more than 10^7 stress cycles at the limiting stress range.

The results of series 5, 6, 10 and 11 are shown plotted on semi-logarithmic co-ordinates in Fig. 9, giving a comparison between milling (or lathe-cutting) and form rolling for 1-in. diameter bolts. Fig. 10 shows the S-N curves for series 5, 7, 10, 12, 14 and 15 showing the effect of root rolling with a 350lb. roller load on three mild steels of different composition. Fig. 11 shows the S-N curves for series 10, 12 and 13, showing the effect of varying the degree of root rolling. Fig. 12 shows endurance plotted against roller load for root rolled 1-in. bolts of the second composition when each of the specimens was subjected to the same stress cycle of 3 to 16 tons/sq. in.

There was only one compound fracture in the 1-in. size and this also was on a specimen which was tested again at a higher stress level after remaining unbroken at more than 10^7 stress cycles. This re-testing procedure was adopted on a few occasions owing to the limited number of specimens available; it had to be used with great discretion as there

TABLE IV.—SUMMARY OF FATIGUE STRENGTH RESULTS.

Method of thread production	3-in. diameter bolts		1-in. diameter bolts	
	Limiting stress range* tons/sq. in. Minimum stress, 3 tons/sq. in.	Fatigue strength, per cent.	Limiting stress range* tons/sq. in. Minimum stress, 3 tons/sq. in.	Fatigue strength, per cent.
First composition (C. 0·16 per cent., Mn. 1·0 per cent.)				
High speed, semi-automatic lathe	4·5 (5·25±2·25)	100	—	—
Ground	3·9 (4·95±1·95)	87	—	—
Milled	4·5 (5·25±2·25)	100	—	—
Form rolled (series 4 and 6)	10·9 (8·45±5·45)	240	14·5 (10·25±7·25)	240
Lathe cut (series 5)	—	—	6 (6±3)	100
Lathe cut and root rolled (350 lb. roller load)	—	—	13·5 (9·75±6·75)	225
Second composition (C. 0·15 per cent., Mn. 0·5 per cent.)				
Milled (series 8 and 10)	3·5 (4·75±1·75)	100	4·5 (5·25±2·25)	100
Form rolled	10·25 (8·125±5·125)	293	10·5† (8·25±5·25)	235†
Milled and root rolled (350 lb. roller load)	—	—	11·0 (8·5±5·5)	245
Milled and root rolled (250 lb. roller load)	—	—	10·5 (8·25±5·25)	235
Third composition (C. 0·2 per cent., Mn. 0·64 per cent.)				
Milled	—	—	6·5 (6·25±3·25)	100
Milled and root rolled (350 lb. roller load)	—	—	14·5 (10·25±7·25)	223

* Stresses are based on thread-root area.
† True endurance limit not obtained owing to scatter.

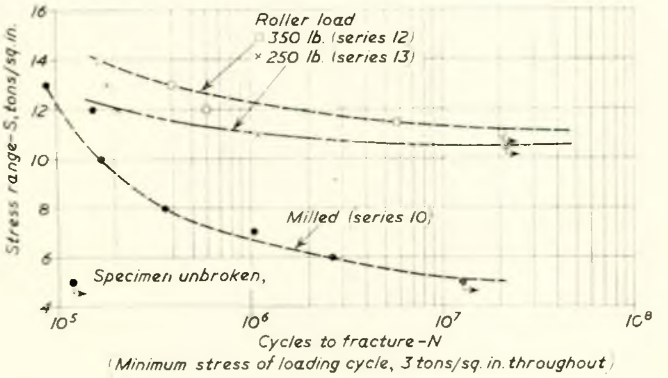


FIG. 11—*S-N curves for 1in. diameter bolts showing effect of degree of root rolling 2nd composition*

was the possibility that the endurance might be increased by the effect of understressing. In all cases where a point on the S-N curve was obtained by the use of a previously tested specimen, the point is indicated by the letter R.

From earlier experimental work it may be accepted that the effect of the variation of mean stress has no significant effect on the values obtained for the safe ranges of stress; this basis has been confirmed by other workers for mild steel, although it does not hold for most other materials. Values of the limiting stress range for each series of bolts tested are therefore given in Table IV.

(4) *Discussion of Results*

It is evident from the small scatter of the results of the fatigue tests plotted in Figs. 7 to 11, compared with those reported by Taylor which are reproduced in Fig. 1, that, with care, it is possible to produce threads of sufficient accuracy to ensure that the fatigue strength is within predictable limits. It should be made quite clear, however, that greater accuracy of thread formation does not necessarily lead to an increase in fatigue strength.

Cut and Milled Threads

It will be seen from Fig. 7 that the plotted results obtained from the tests on bolts with cut (high speed semi-automatic lathe) or milled threads lie on or close to a single curve (A). It would therefore appear that the type and speed of the cutting action has no appreciable effect on the fatigue strength of the material used. In this event there seems to be no reason why the fatigue strength of bolts with accurately machined lathe-cut threads should differ from that for milled or cut threads produced on the high speed semi-automatic lathe.

Whilst too much emphasis should not be placed on limited tests, it is interesting to note from Table IV that there is a consistent value for size effect shown by the results of series 4 and 6 and 8 and 10 and if this is used to translate the results of series 5 from 1-in. diameter to 3-in. diameter, a value for the limiting stress range of 3-in. lathe-cut bolts of 4·57 tons/sq. in. is obtained which compares very well with the value of 4·5 tons/sq. in. obtained experimentally for both the high speed semi-automatic lathe cut bolts and the milled bolts.

It was tentatively suggested by Taylor(1) that test results from accurately formed lathe-cut threads might be expected to fall within the shaded band in Fig. 1, which would have established the limiting stress range between the limits 5·4 to 6·4 tons/sq. in.; examination of Fig. 7 shows this estimate to have been somewhat high. Taylor himself has commented on the errors in thread form and pitch errors of his test bolts and, as will be discussed later, it is likely that these pitch errors accounted for the higher fatigue strength of Taylor's lathe-cut threads.

Ground Threads

Thread grinding has an adverse effect on the fatigue strength. As will be seen from Fig. 7, the results of the tests on ground-thread bolts give the S-N curve B, which lies a little below that for the other bolts tested. The reduction in the limiting stress range, as will be seen from Table IV, amounts to about 13 per cent, a value greater than anticipated. The difference in strength of the ground and cut-thread specimens cannot be attributed to an intrinsic difference in the fatigue strength of the material from which the test bolts were made. The possible formation of surface cracks during the grinding process was also considered but a careful microscopic examination of six bolts failed to reveal any such defects. The most likely explanation for the lower strength of the ground thread bolts is that the grinding process causes some change in the properties of the material by over-heating or "burning" of the surface.

Form Rolling of Threads

It will be seen from Table IV that rolled thread bolts have a fatigue strength some 2¼ to 3 times that obtained with milled or cut threads irrespective of size. This increase is very much greater than anything previously reported in the literature; as mentioned earlier, the material properties to give the best results are obscure, but it is still reasonable to attribute the unexpectedly great increase to some property of the material from which the bolts were made. The manganese-carbon ratios of the two compositions tested were 6·25 and 3·67 which suggests that this ratio does not have a significant influence. However, despite the difference in composition and tensile strength of the specimens, the ratio of yield to ultimate stress varied only slightly for the two materials, the range being 0·52 to 0·61. This ratio may be the criterion of the ability of a material to gain increased fatigue strength from thread rolling.

An important point brought out by these tests is that particular care is required in the design of bolts with rolled threads to obtain uniform strength at different sections. This applied particularly to the fillet radius under the head.

Root Rolling of Threads

It will be seen from Table IV that the increase in the limiting stress range of 1-in. bolts produced by rolling the thread roots after cutting or milling was practically as great as that resulting from form rolling of the threads. In view of the apparent lack of size effect on the percentage increase of fatigue strength indicated by the results from the form rolled specimens of both sizes, it seems probable that similar results could be attained by after-rolling the threads of bolts larger than those tested. This demonstrates that the beneficial

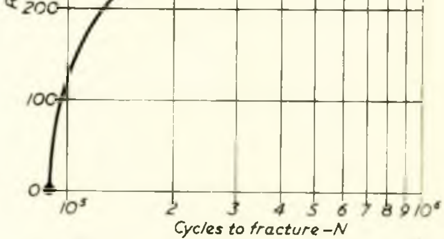


FIG. 12—*Graph of roller load/endurance for 1in. diameter bolts 2nd composition*

effect of thread rolling can be secured by the use of fairly simple and inexpensive equipment; the actual process of rolling after cutting the thread can be carried out rapidly and would add very little to the cost of production. However, where the number of components produced would justify its use, the form rolling process has the great advantage of speed and cheapness of manufacture.

The tests to ascertain the effect of roller load (Fig. 12) showed that fatigue endurance increased with roller load up to an optimum value, with a rapid falling off in endurance when this load was exceeded. Fig. 11 also demonstrates the effect of the degree of root rolling and gives good confirmation of the deduction from Fig. 12. It is noteworthy that the S-N curves in Fig. 11 for 250lb. and 350lb. roller loads gave results with a small degree of scatter but when tests were made with specimens root rolled at 400lb. roller load there was so much scatter of results that an S-N curve could not be produced. The fatigue curve for the 1-in. form rolled specimens of the second composition (Fig. 9) also shows a great deal of scatter particularly when compared with the 3-in. form rolled specimens of the same composition and it is suggested that the 1-in. form rolled specimens may have been overworked during the form rolling operation.

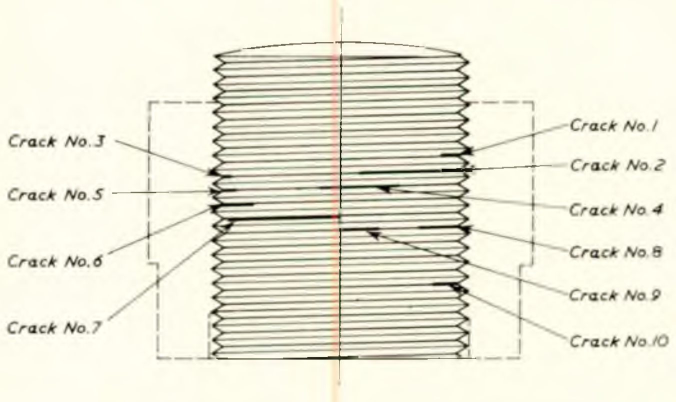
The fatigue curves for specimens root rolled with 350lb. roller load (Fig. 10) show that this roller load is suitable for mild steels within the range of composition tested, giving a fairly consistent increase in fatigue strength, whilst Figs. 11 and 12 indicate that rather lower roller loads may well be almost as beneficial. If mild steels of markedly different compositions are used, tests to determine the optimum roller load would appear advisable.

Effect of Pitch Errors

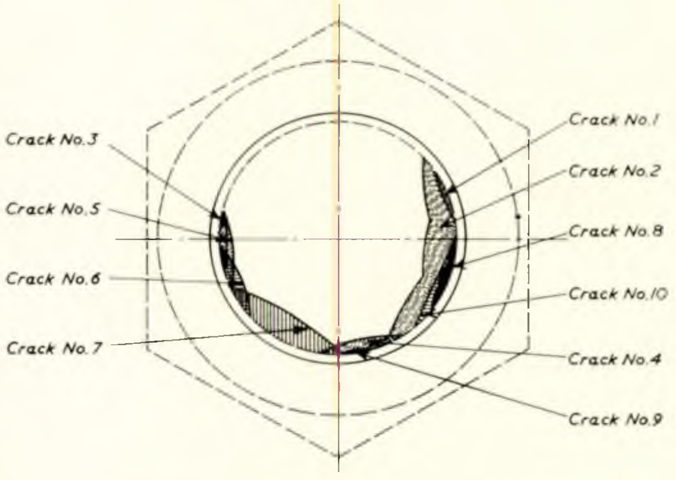
It was shown by Taylor$^{(1)}$ that the effect of the mean stress of the loading cycle on the limiting stress range of un-notched mild steel specimens is of little significance particularly at low mean stress values. From laboratory tests the endurance limit for polished un-notched mild steels can reasonably be taken as the ultimate tensile strength of the material. In this case it is possible to predict the theoretical limits of fatigue strength for bolts having accurately machined threads. It has been shown earlier that for the 3-in. test bolts the overall stress concentration factor has a value of 6·8 for accurately formed threads of uniform pitch and diameter; as this value is a maximum it gives rise to the minimum value for the limiting stress range, which is then given by $\frac{33\cdot2 - 3\cdot0}{6\cdot8} = 4\cdot44$ tons/sq. in. for bolts of the first composition and $\frac{26\cdot24 - 3\cdot0}{6\cdot8} = 3\cdot42$ tons/sq. in. for bolts of the second compostion. These theoretical results are in very close agreement with the experimental values of 4·5 tons/sq. in. obtained from series 3 (1st composition) and 3·5 tons/sq. in. obtained from series 8 (2nd composition), and therefore support the argument that threads of accurate pitch give the minimum fatigue strength.

The maximum fatigue strength would be obtained if the difference in pitch of the mating threads was such as to produce an inverse thread-load distribution which, combined with the form s.c.f., would result in a uniform stress along the root of the thread helix. Under such conditions the thread-root stress would at no point exceed that caused by the notch effect of the thread (nominal axial core stress × form s.c.f.). It has been shown earlier that for the 3-in. test bolts the form s.c.f. has a value of 3·5 and the maximum theoretical limiting stress range is $\frac{33\cdot2 - 3\cdot0}{3\cdot5} = 8\cdot6$ tons/sq. in. for bolts of the first composition (series 3) and $\frac{26\cdot24 - 3\cdot0}{3\cdot5} = 6\cdot6$ tons/sq. in. for bolts of the second composition.

It is interesting to note that the theoretical maximum limiting stress range for the bolts in Fig. 1 is 8·2 to 8·4 tons/sq. in. whilst the maximum experimental value was 7·6 tons/sq. in. At the same time the theoretical minimum limiting stress range for the bolts in Fig. 1 would be 4·2 tons/sq. in. compared with the experimental value of 4 tons/sq. in.



SIDE VIEW OF BOLT SHOWING POSITION OF CRACKS



END VIEW OF BOLT SHOWING DEPTH OF CRACKS

FIG. 13—*Multiple cracks in 3-in. test bolt with large positive pitch error*

After 10,210,300 cycles, 0·1 to 7 tons/sq. in.

The results obtained from the bolts tested with nuts having tapered threads are in complete agreement with the hypothesis stated previously. An endurance of 1,350,000 cycles at a stress range of 7 tons/sq. in. was obtained from the assembly with a positive pitch error, while the assembly with a negative error gave an endurance of 558,000 cycles at the same stress range. From the S-N curve for accurately machined threads the corresponding endurance is 520,000 cycles; it will be noted that this endurance is slightly less than that of the assembly with the negative pitch error. Both nuts had a taper equivalent to a pitch error of 0·0016in. per inch, but small pitch errors were present in the bolts. Taking these into account the effective pitch error of the improved nut was + 0·0013in. per inch and of the worsened nut − 0·0014in. per inch. Both fractures were of the simple type, which indicates that the analysis set forth in Fig. 3 would class the errors as medium.

During a series of tests, the results of which are not included in this paper, a 3-in. bolt, which had been thread-cut on a high-speed semi-automatic lathe, when tested also at a stress range of 7 tons/sq. in., remained unbroken after more than ten million cycles, that is, some seven times the endurance of the assembly with the improved nut. Unfortunately this particular test bolt was not checked for accuracy, but there was evidence that a variety of pitch errors were present in the batch; two bolts from the batch which were measured had pitch errors equivalent to positive errors of the order of 0·001 to 0·0015in. per inch. This bolt with the long endurance probably represented the case in Fig. 3 of the large positive pitch error range because examination after testing revealed the crack formation shown in Fig. 13. The original crack (No. 1 in Fig. 13) had occurred near the free face of the nut, re-distribution of the load towards the loaded end had proceeded in stages as postulated earlier and no less than ten cracks had formed before the test was terminated.

The results indicate that a positive pitch error of just over 0·001in. per inch is sufficient to effect a considerable increase in endurance and possibly an appreciable increase in fatigue strength. Insufficient information is available, however, to fix the limit at which pitch errors become large, i.e. sufficient to cause compound fractures, but it seems likely that they would have to be considerably greater than 0·001in. per inch.

Accuracy of Thread Forming Methods

The number of specimens examined in detail was small and care has therefore been necessary in drawing any general conclusions on the relative accuracy of the different methods of thread forming. The accuracy of a thread produced by any machine obviously depends on the condition of the machine, but some types are more liable to introduce errors than others. The observations which follow are considered, however, to be justified by the examinations made in the course of this investigation.

It is generally accepted that modern thread grinders have reached such a stage of perfection that errors may be reduced to negligible proportions and this was borne out by the specimens examined in the present work. However, this is a costly process and unless an equally accurate method of producing the internal threads of the nut is adopted there is no point in grinding the threads of the bolt. So far as is known, internal thread grinding is not used as a production process unless hardened steel is used.

Thread milling is a process capable of producing reasonably consistent and accurate work for both internal and external threads, and it has the advantage that a semi-skilled operator can handle the machine.

Normal production lathes cannot be relied upon to produce threads of such accuracy that the distribution of load along the threads is not liable to vary from one bolt to another.

The high speed, semi-automatic lathe is capable of producing threads of considerable accuracy but it does not appear, however, that consistent results can be guaranteed from one machine to another or even on the same machine. Work from three machines of this type has been examined; pitch errors tend to be of an erratic nature and may reach relatively large values. On the other hand, a high quality finish is produced and in the specimens examined the threads were accurately formed. As pitch errors are of no great consequence this method of production possesses many advantages over others.

Extremely accurate thread forms and a high quality surface finish are produced by the thread rolling process.

The accuracy of threads rolled in the roots is, of course, dependent on the accuracy of the initial thread-machining method but the process of root rolling increases the pitch of the threads and after root rolling threads may have to be chased to relieve diametral and pitch tightness.

5) *Conclusions*

The fatigue strength of a bolt and nut assembly produced by any given thread-forming method is largely dependent upon the accuracy with which the threads are formed. However, there is no direct relationship between accuracy and fatigue strength. Inaccuracies in pitch which are liable to occur in normal production work do not cause any reduction in fatigue strength but may, on the contrary, increase it. On the other hand, errors in form and poor finish of threads may cause a loss of strength. Errors in flank angle are particularly objectionable since they will offset the line of loading of the threads and consequently affect the fatigue strength of the bolt.

There is little to choose between the different methods of thread cutting from the point of view of fatigue strength, provided that the resulting form and finish of the threads is good. Thread grinding is not to be recommended for dynamically loaded bolts.

Striking improvements in fatigue strength are obtained by the form rolling of threads; the fatigue strength of forged mild steel bolts may be increased to 2½ to 3 times that of a cut thread.

Almost as great an increase in fatigue strength can be obtained by a simple root rolling process applied to threads which have been cut to good form and a good finish by any of the normal thread-cutting methods. There is an optimum roller load which is not very critical but should preferably be determined for any material of composition markedly different from those reported here.

A positive pitch error of the nut, i.e. a lengthening of pitch, of just over 0·001in. per inch or a corresponding negative pitch error in the bolt is sufficient to effect a considerable increase in endurance and possibly in fatigue strength. It does not appear to be practicable in the marine engineering industry, however, to produce screwed components with intentional pitch errors or tapered threads with the object of increasing the strength. Negative pitch errors in the nut or positive pitch errors in the bolt have little effect but it is possible that bolts of high-strength steel might not show the insensitivity to negative pitch errors that is exhibited by mild steel.

Information is far from complete regarding the influence of size of the bolt and pitch of the threads and the quantitative results cannot readily be applied to bolts of different size and material. However, the results of this investigation suggest that a close estimate of the fatigue strength of large mild steel bolts can be made by application of the theoretical stress concentration factor.

Of the different thread-forming methods examined, grinding, milling and rolling appear capable of producing external threads of consistently accurate pitch. Although the test bolts which were thread-cut on a high speed, semi-automatic lathe gave good results subsequent experience has shown that this type of machine is liable to introduce pitch errors in both external and internal threads; such pitch errors, however, will not reduce the fatigue strength. All these methods produced threads of good finish and accurate form superior to lathe-cut threads.

ACKNOWLEDGEMENTS

The authors' thanks are due to the Council and Director of Research of the British Shipbuilding Research Association for permission to publish this paper.

The authors are particularly grateful to Mr. Bryan Taylor and Mr. W. F. Dowie for all their work in providing the data on which this paper is based.

REFERENCES

1) TAYLOR, B. 1952. "The Strength of Large Bolts Subjected to Cyclic Loading", Trans.I.Mar.E., Vol. 64, p. 233.
2) NEUBER, H. 1945. "Theory of Notch Stresses", David Taylor Model Basin, Transaction No. 74.
3) HEYWOOD, R. B. 1952. "Designing by Photo-Elasticity". Chapman and Hall, Ltd., London.
4) SOPWITH, D. G. 1948. "The Distribution of Load in Screw Threads", Proc.I.Mech.E., Vol. 159, p. 373.
5) PHILLIPS, C. E. and HEYWOOD, R. B. 1951. "The Size Effect in Fatigue of Plain and Notched Steel Specimens Loaded under Reversed Direct Stress", Proc.I.Mech.E., Vol. 165, p. 113.
6) STOECKLY, E. E. and MACKE, H. L. 1952. "Effect of Taper on Screw Thread Load Distribution", Trans. A.S.M.E., Vol. 74, p. 103.
7) WIEGAND, H. 1934. "Uber die Dauerfestigkeit von Schraubenwerkstoffen und Schraubenverbindungen". Dissertation der Technische Hochschule, Darmstadt, p. 35.
8) BOLLENRATH, F. and CORNELIUS, H. 1947. "Einfluss der Gewindeherstellung auf die Dauerhaltbarkeit von Schrauben". Werket. u.Betr., Vol. 80, p. 217.

9) MOORE, H. F. and HENWOOD, P. E. 1934. "Strength of Screw Threads under Repeated Tension". Bull. Univ.Ill. Engng. Exp. Sta. 264.
10) DINNER, H. and FELIX, W. 1945. "Rolling of Screw Threads", Sulzer Tech. Rev: No. 1, p. 321.
11) 1951. "Gauging and Measuring Screw Threads", National Physical Laboratory, Notes on Applied Science No. 1, H.M. Stationery Office.

Written Discussion

MR. H. ERNST wrote that this interesting paper had shed new light on bolts of large diameter. The root rolling was efficient as well as original and he considered that this method deserved further investigation and development.

The authors had shown the influence of small pitch variations and had emphasized the importance of the accuracy of the profile and the quality of the thread surface; however, they had referred especially to the bolt thread whilst, in his experience, the thread in the nut was also important. In fact, on form rolled bolts, he had improved in some measure the fatigue strength by improving the accuracy of the nut thread; of course the tap and the tapping operation had to be adequate.

His company was very much in favour of profile rolling which was an economic and accurate process; it guaranteed an almost perfect pitch and the required quality of the thread surface, but care had to be taken not to overdo the rolling as this was liable to make the core brittle.

The results of various fatigue tests were shown in Fig. 14, and it would be seen that since 1952 the strength had been gradually increased. The best results up to now on the 64 mm. metric thread were obtained with bronze nuts. In tests using bronze nuts the bolt did not break in the thread portion as was usual with steel nuts, but in the shank, the cross-sectional area of which was 90 per cent of the core section of the threaded portion.

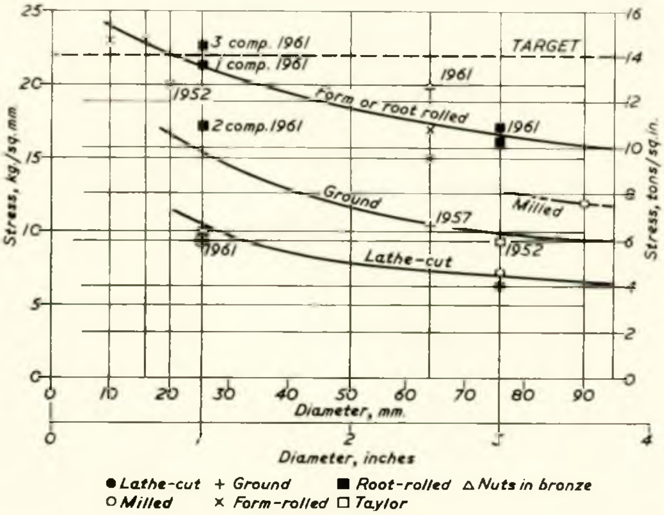


FIG. 14—*Variation of fatigue stress thread forming methods*

He believed that the old expression "size effect" had lost some importance and that it might even disappear on the day that one was able to produce a really accurate thread for large bolts, and when the optimum pitch for each diameter was known.

He would be interested to learn why the authors persisted in using for the 3in. bolts a special thread of 6 t.p.i. as this did not correspond either with the standard 3½ t.p.i. Whitworth or the 5 t.p.i. British Standard Fine thread. In fact, he felt that with 5 t.p.i. the authors would get a slightly better result. Of course, on the Continent they preferred the unified ABC Washington 60 deg. profile, created by America, Britain and Canada, to the Whitworth profile. The former (at least the geometric form of it) was now adopted also by the International Standardization Organization, that is to say by all the "metric" countries. This profile was advantageous for the tool maker as well as for the manufacturer of threaded components. Also, the results of static and dynamic tests on bolts with the Washington profile were at least as good as those on bolts with the Whitworth profile.

MR. I. HOLMAN felt that the whole of Section 1 dealt with the effect of pitch errors, concluding finally, that from the point of view of fatigue failures they did not matter. At the same time little was said about malformed threads or the effect when a good thread was cut into a nut with a malformed, i.e. a tapered or an eccentric hole.

His company, of course, had no experience of such large diameter bolts as the authors were considering, and perhaps it was the case that 3in. diameter bolts and nuts would be threaded on a screw cutting lathe, using a single point tool, in other words, a single tooth chaser. Under these conditions it might be that pitch errors were more likely than malformation.

In the production of those sizes of bolts and nuts, where thread rolling and nut tapping were used, while pitch errors in bolt threads could be induced by faulty dies or die setting, and in nuts by the use of taps containing pitch errors, these should not normally occur, whereas malformed threads especially in nuts, were possible under poor production conditions.

Differing methods of production, therefore, limited the significance of this report to the larger components—as was, its title—excluding the numerically much more important field of smaller sized thread production.

The worsening of fatigue values, when thread grinding was used, was surprising, since the form obtained should be satisfactory, but it did not seem clear, from the report, whether the grinding was used merely for finishing a partly cut thread, or for forming the entire thread from a cylindrical blank.

If the latter was the case, it was felt that grinding was hardly the best means of major metal removal, especially on such soft materials, and surface deterioration might well occur.

It was thought that the report was interesting and probably valuable, when the threading of the large bolts to which it referred, was being considered.

MR. R. F. HOLMES writing on behalf of Mr. Trowbridge, said that while the automotive industry was mainly interested in sizes below one inch, the finding in the paper for larger size bolts would generally also apply to sizes below one inch.

The special design and manufacturing problems for the sizes above one inch were not applicable to automotive practice. Bolts in sizes below one inch were usually made by cold forming the heads and extruding the shanks for the thread rolling process. This resulted in full body diameter between the end of the thread and the head. In application of bolts of this type, the length of exposed thread between the nut and bolt head had an important effect upon the bolt fatigue strength.

In reviewing the paper, the thought had occurred to him of what would happen to ground thread samples if they had also been root rolled. Root rolling had been advocated for cut, ground or rolled threads by Mr. J. O. Almen in his article*.

He noticed the statement on page 425, "The third bolt tested in series 4 remained unbroken after being subjected to 10 million cycles at a stress range of 11 tons/sq. in., etc.". On page 420, it mentioned "(the nuts used) for series 4 corresponding values were 26·0 and 35". Since the nut material used with series 4 bolts was 26·0 tons/sq. in., the statement on page 425, ". . . no fatigue cracks had been formed in the bolt, but several were found in the nut threads . . .", might be accounted for by cold-work of the nut material in loading the nut.

The statement on page 417 "inaccuracies in pitch do not cause any reduction in fatigue strength, but may on the contrary, increase it", does not limit the type of lead deviation as does the statement on page 418 "that a positive pitch error of the nut or negative pitch error of the bolt threads has the beneficial effect of removing the point of load concentration from the loaded face of the nut". This condition had long been considered beneficial in bolt and nut applications where the bolt thread lead increased and the nut thread lead decreased due to the bolt tension load.

Tapering the thread in the nut so that the smaller diameter was at the "free end" had been advocated†.

The paper covered many of the known methods of improving the fatigue strength of bolts and by incorporating the stress range principle in the fatigue testing of bolts, should serve as a guide for future tests. The non-uniformity of testing methods used in reports on fatigue tests of bolts detracted from their value.

He was pleased to have the opportunity of reviewing the paper and trusted his comments would be helpful.

Mr. P. Leo wrote that he had read the paper with considerable interest.

He regretted that he had nothing to contribute by way of discussion on the paper apart from the observation that the low fatigue strength of large ground bolts surprised him.

The low fatigue strength of small ground thread studs was known, but he had not realized that this was true for large diameters also. The thought had occurred to him that even with turning and milling there was a small amount of burnishing of the root due to the pressure between the work and the clearance angle of the cutter, and this might well improve the fatigue strength of bolts produced in this way over that of grinding.

Mr. R. Liffen wrote to say that he had been interested by the paper prepared by Mr. Cook and Mr. McClimont.

The maximum rolled thread diameter : pitch ratio used by his company was $\frac{11}{16}$: 11. On the larger threads produced by milling or die head chasers, they had not found the necessity to root roll, threads were invariably of the 16 pitch series, and in the majority of cases were produced with a root radius. Where threads were ground, a root radius was also formed.

They had a strict control on the half angles of thread producing tools, and would not deliberately set out to produce lead errors in such tools to increase fatigue strengths of threaded components. The fact that lead errors invariably existed was accepted.

Three inch diameter bolts were rather outside his company's range of size, but he well understood the need to root roll these threads for marine engineering use.

Mr. A. C. Low, B.A., in his contribution, wrote that the authors were to be congratulated on showing that the superior fatigue strength of cold rolled threads, already well known in respect of smaller sizes, extended to the larger sizes common in the marine and heavy electrical field. Equally important was the demonstration that form rolling was not essential; root rolling with a simple fixture gave equally good results. It might be felt that the authors had been unnecessarily cautious in their use of the word "practically" in the paragraph headed "Root Rolling of Threads". In bolts of large diameter adequate pre-tensioning on assembly, in order to reduce the proportion of any dynamic load on the assembly carried by the bolt, was a practical impossibility in most cases, and any improvement in fatigue strength that could be obtained was to be welcomed. The authors' preoccupation with threads of good form and good finish was perhaps unfortunate. A comparison of cut threads of poor finish and inadequate root form with similar threads after root rolling might have been even more enlightening.

The occurrence of cracked nut threads in one specimen was unusual, but not entirely unknown. Dimensional considerations normally showed the nut thread to be substantially stronger than that of the bolt. It might be significant that it was a form rolled bolt which produced this result, where the whole of the thread triangle might be expected to have some increase of strength. Similar failures had been experienced at the National Engineering Laboratory on the specimen-gripping heads on a fatigue testing machine.

A further point worth considering when comparing ground and cut threads was the possibility that the cut threads were, in fact, slightly work hardened. It had been repeatedly found at N.E.L. that, to obtain results on notched specimens consistent with plain specimens and notch s.c.f., required a stress relieving heat treatment after cutting the notch, no matter how carefully this was done.

Increases in strength by cold rolling of the same order as those reported here were obtained in NPL/NEL researches in connexion with the introduction of the Unified Thread Form. Fig. 4 and Table I in the paper‡ by Sopwith and Field gave results for $\frac{3}{4}$in. diameter bolts that agreed well with some of the authors' results when adjusted for differences in tensile strength.

The assertion that the endurance limit for polished unnotched mild steels could be taken as the tensile strength was open to question. That the endurance range at zero mean stress was of this order and that mean stress had no effect could be admitted, but when the upper stress of the cycle reached the yield, the picture was modified. While some satisfactory correlation with test data had been produced, it might be felt that the basis on which the calculations were made was doubtful.

Professor A. I. Yakushev wrote that this paper was particularly valuable since the fatigue strength was determined on screwed connexions of large dimensions and simultaneously a great number of technological factors, as well as factors affecting accuracy, was investigated. In this respect the data yielded by the investigation were quite unique. He would like to draw attention to the experience which he had gained in carrying out similar investigations and to point out some

---

* Almen, J. O. April 1951. "Fatigue Durability of Pre-stressed Screw Threads". Product Engineering (U.S.A.).

† Eltham, B. E. August 1950. "New Light on Bolted Joints". Mechanical World (British) p. 127.

‡ Sopwith, D. G. and Field, J. E. May 1957. "The Unification of Screw Thread Practice". The Engineer, Vol. 203, pp. 793-795.

special features for the authors' consideration. His book,* which had been published in Moscow in 1956, would be published in English by Pergamon Press in 1961 and in the observations which followed he would make appropriate reference to this book.

His investigations had shown that the fatigue strength of threaded connexions was greatly influenced by the dimension of the root radius of the bolt thread (Table III-3, Figs. III-5 and III-6),* by the smoothness of the root contour (Fig. III-7 and text on page 73)* and by clearances that might exist at the thread diameters and especially at the minor diameter (Tables IV-5, IV-6, Fig. IV-1 and text on pp. 91-96).* It would therefore be desirable to quote in the paper data regarding the actual dimensions of the thread of the tested bolts and nuts, as he had done in Tables III-1 and IV-1 of his book.

In his investigations, both positive and negative deviations of the bolt pitch from the pitch of the nut had caused a lowering in the fatigue strength of threaded connexions (Table V-5, Figs. V-1 and V-2).* This was due to the fact that with such deviations the distribution of stresses over the turns of the thread within the length of the threaded connexion became less uniform. If the pitch of the bolt thread were greater than that of the nut thread, then, after a preliminary tightening, when external load was applied, the deviations of the pitch of the bolt thread increased still further owing to the extension of the bolt and the compression of the nut, and the distribution of stresses over the turns of the thread became still more uneven. As was known, with a considerable unevenness in stress distribution the load on the first and second working turns of the bolt was increased, which lowered the strength of threaded connexions (Table V-5).*

If the pitch of the bolt thread were smaller than that of the nut thread, a load applied to the threaded connexion might result in reducing the pitch inequality. It was theoretically possible to determine the reduction in the pitch of the bolt thread, or the increase in the pitch of the nut thread, such that the difference in the deformations of the bodies of the bolt and nut would not be passed on to their threads. In this case, the stress distribution was more uniform. The most favourable positive difference, ΔS, between the pitch of the bolt and that of the nut was determined from the condition of stress equality in the upper and lower turns of the thread, which gave the following expression for ΔS

$$\frac{\Delta S}{S} = \frac{P}{2}\left(\frac{1}{E_1F_1} + \frac{1}{E_2F_2}\right)$$

where,

P = load extending the threaded connexion

E_1, E_2 = moduli of elasticity of bolt and nut

F_1, F_2 = cross-section areas of bolt and nut

It could be seen that for each load P there was a corresponding optimum value of ΔS. The most favourable pitch difference ΔS depended also on the modulus of elasticity of the material and on the dimensions of the bolt and nut.

If $E_1 = E_2 = E$, we had

$$\frac{\Delta S}{S} = \frac{\sigma_1 + \sigma_2}{2E}$$

Now if $\sigma_1 = \sigma_2 = 2{,}000$ kg./sq. cm. and $E = 2 \times 10^6$ kg./sq. cm., we found

$$\frac{\Delta S}{S} = 0{\cdot}001.$$

This meant that in the case of thread with $S = 1$ mm. we had $\Delta S = 1\mu$, in the case of a thread with $S = 3$ mm. the difference was $\Delta S = 3\mu$, etc. This pitch difference was so small that it was difficult to realize it in practice.

In view of this, the conclusion that pitch errors had no adverse influence, and sometimes even increased the fatigue strength of threaded connexions, ought to have been more accurately worded and checked by producing increasing pitch errors of the bolt, and not by producing a taper of the thread which, in itself, caused a certain increase in the strength. In his opinion certain small pitch errors were admissible.

In his investigations, both positive and negative deviations of the flank angle of the bolt thread from that of the nut thread, or *vice versa*, had resulted in an increase of the fatigue strength of threaded connexions (Table V-5, Fig. V-3 and text on pp. 103-106).*

The conclusions of the authors regarding the advantage of rolled and cut bolt threads with smooth roots were in agreement with the results of his own investigations. In this connexion it would be desirable if the authors would give data regarding the conditions under which the threads had been formed, as well as the surface roughness and micro-hardness of the material of the bolts before the test (similar to the information he had given in Figs. VII-2 to VII-19 and Table VII-2 of his book), since these determined the fatigue strength of screwed connexions (Tables VIII-3, VIII-4, VIII-5, VIII-7, VIII-8 and VIII-10).*

---

* "The Influence of the Technology of Manufacturing and of the Basic Thread Parameters on the Strength of the Threaded Connections".

Authors' Reply

The authors were gratified by the amount of discussion provoked by their paper and wished to thank the contributors. When the British Shipbuilding Research Association began to formulate its research programme some sixteen years ago, it was realized that the strength of dynamically loaded large bolts merited attention. Failures of such bolts occurred from time to time in marine oil engines with results which were usually expensive. There was a dearth of information concerning the fatigue strength to be expected from those components and the influence of design and method of manufacture. The results given in the present paper formed part of the investigation which followed and it was felt that they went some way to filling those gaps in our knowledge.

In reply to Mr. Ernst they thought that his confirmation of the value of form and root rolling and the importance attached to these processes by the famous oil engine manufacturers, which he represented, were valuable. His comments on the value of improving the accuracy of nut threads were also most interesting. In their own investigation the authors had, at the outset, deliberately sorted out the most accurate method of forming nut threads with a view to eliminating this variable.

The choice of six threads per inch for the three inch diameter bolts was due to the fact that it was considered to be the normal practice in the industry at that time. Some tests had already been made regarding the influence of pitch and the question of further tests was under consideration. Meanwhile, the comment of Mr. Ernst regarding the use of 5 t.p.i. was noted with interest as also were his comments regarding standardization of profile. The advantages of standardization were, of course, very great and the advent of the Common Market might well hasten its wider application.

Mr. Holman raised the question of the effect of malformed threads. Here again, the authors deliberately set out to eliminate this variable, but throughout the paper emphasis had been laid upon the importance of good form and finish of threads.

The reduction in the limiting stress range due to thread grinding referred to by Mr. Holman was not altogether unexpected by the authors since the fatigue limit of ground specimens was usually found to be lower than that of comparable polished test pieces. What they had found surprising, however, was the amount of the reduction, namely, some 13 per cent. Tests by Cledwyn-Davies* showed that the reduction in fatigue strength of ground mild steel specimens compared with those turned and polished amounted to only 3½ per cent. The same author had shown that surface tensile stresses caused by grinding were not of major importance; he concluded, however, that normal production grinding was likely to cause "burning" of the surface. This seemed to be a likely explanation of the lower strength of the ground thread bolts. Mr. Leo and Mr. Low put forward an alternative explanation that work hardening might cause an increase in fatigue strength in the case of cut threads.

Replying to Mr. Holmes the authors noted that he rightly differentiated between the design and manufacturing problems applicable to automotive practice and those applicable to marine engineering, but they agreed that many of the findings were applicable irrespective of size.

Although both theory and experiment indicated that a positive pitch error of the nut was beneficial to fatigue strength, the use of this feature was not considered practical in the marine engineering industry.

Mr. Leo had also commented upon the fatigue strength obtained with ground thread bolts and the authors would refer to the reply to Mr. Holman. Burnishing of the thread roots in turning and milling might well, as he suggested, be effective in this phenomenon.

The authors were indebted to Mr. Liffen for his remarks and noted that he would not consider introducing pitch errors in the sizes with which he dealt. This was in accordance with the general view of the marine engineering industry with regard to larger sizes.

The authors were particularly glad to have Mr. Low's contribution in view of his great experience in this field of research. His criticism regarding the use of the term "practically" in the paragraph regarding root rolling was accepted. The authors also agreed that a comparison of cut threads of poor finish and inadequate root form with similar threads after rolling would have been enlightening. No one knew better than Mr. Low, however, that work of this nature was time consuming and expensive, especially in the larger size of bolt, and that it was, therefore, necessary to restrict the number of variables under investigation.

The authors were indebted to Professor Yakushev for his contribution and awaited with interest the publication of his book in English.

In the original reports upon which the present paper was based, considerable attention was given to thread examination but the results were omitted from the present paper for reasons of space.

It was clear that Professor Yakushev's experience regarding the influence of pitch errors was at variance with that of the authors. Professor Yakushev did not, however, give particulars of the type of steel employed in his investigations and the authors wondered whether in fact he employed high tensile steels. If so, it would appear that this might account for the observed differences in the two sets of results. It would be noted that the authors' experiences were based upon the use of mild steel and the occurrence of a certain amount of local yielding.

---

* Cledwyn-Davies, D. N. 1955. "The Effect of Grinding on the Fatigue Strength of Steels". Proc.I.Mech.E., Vol. 169, p. 83.

INSTITUTE ACTIVITIES

Section Meetings

Devon and Cornwall

Junior Meeting

A Junior Meeting of the Devon and Cornwall Section was held on Tuesday, 7th November 1961 at the Technical College, Falmouth at 7 p.m.

A lecture entitled "The Layout and Operation of Marine Steam Turbine Machinery" was delivered by Mr. D. M. V. Parkinson, M.V.O. (Member) before an appreciative audience of about seventy which included technical students, engineer apprentices and members of the Institute.

The lecture was well received and the thanks of all those present were voiced by Mr. C. Moffatt (Local Vice-President) who, at the same time, mentioned that the Devon and Cornwall Section was now established. Mr. Moffatt then introduced Mr. W. E. B. Dainton (Chairman of the Section) and Mr. A. H. Morton (Honorary Secretary) who had travelled from Plymouth for the occasion.

Kingston upon Hull and Humber Area

A meeting of the Kingston upon Hull and Humber Area Section was held on Thursday, 16th November 1961, at the Royal Station Hotel, Kingston upon Hull, when Captain A. Lynas read his paper entitled "Marine Salvage". Mr. Bryan Taylor, B.Sc. (Chairman of the Section) presided at the meeting at which a large number was present. Captain Lynas, who is the Chief Salvage Officer of a leading salvage association, described the unique problems which arose during the recent salvaging of the s.s. *Mary P. Cooper* in the Manchester Ship Canal. The paper was illustrated with a collection of colour slides which depicted the salvage operation step by step. A most interesting discussion followed which covered all aspects of salvage work and was thoroughly enjoyed by all those present.

A vote of thanks to the author was proposed by Mr. F. T. Green (Member).

North East Coast

Junior Meeting

A Junior Meeting of the Section was held on Thursday, 16th November 1961, at the Sunderland Technical College. The meeting had been planned for 4.15 p.m. but owing to a train derailment the lecture was delayed until the arrival of the lecturer.

The intervening time was suitably filled with a talk on the activities of the Institute and the Section.

Mr. D. M. V. Parkinson, M.V.O., then delivered his paper "The Layout and Operation of Marine Steam Turbine Machinery" to a very appreciative audience of the Sunderland Technical College Engineering Society. The meeting was organized by the Head of the Engineering Department of the College Mr. D. Tagg, B.Sc. (Associate Member).

The Institute was represented by Mr. J. G. Gunn, B.Sc. (Corresponding Member), Mr. W. Embleton (Member) and Mr. A. J. S. Bennett, M.B.E. (Honorary Secretary).

Scottish

Joint Meeting

A joint meeting with the Aberdeen Mechanical Society was held at Robert Gordon's Technical College, Aberdeen on Friday, 17th November 1961 at 7.30 p.m.

Mr. W. L. Symon, President of The Aberdeen Mechanical Society, welcomed Mr. J. W. Bull (Chairman of the Section), Mr. J. H. King and Mr. A. W. Clark (Secretary of the Scottish Section) and also the Local Vice-President, Dr. A. C. West, B.Sc., after which he asked Mr. Bull to preside.

Mr. Bull introduced Mr. H. F. Close, B.Sc. (Associate Member), who then read his paper "Elementary Nuclear Engineering" and this was very well received by the 50 members and visitors present.

An interesting discussion followed, which was ably dealt with by the author.

A vote of thanks to Mr. Close for presenting such an instructive paper was proposed by Mr. Hampson and carried with enthusiasm.

Joint Meeting

A joint meeting with the Institution of Engineers and Shipbuilders in Scotland was held on Wednesday, 6th December 1961, at 39 Elmbank Crescent, Glasgow, at 7.30 p.m.

Mr. J. W. Bull (Chairman of the Section) presided, and after extending a particular welcome to Mr. Iain Stewart and Mr. P. W. Thomas, President and Secretary respectively of the I.E.S., introduced Mr. R. Beattie (Member of Committee) who then read his paper entitled "Modern Harbour and Coastal Tugs". This was followed by two films which showed the construction of tugs at many stages and, in general, towing operations.

The paper, the films, and tug models on display proved of exceptional interest and Mr. Beattie also dealt in a very agreeable manner with the various questions raised in the discussion.

In proposing a vote of thanks to Mr. Beattie, which was carried enthusiastically, Mr. Iain Stewart congratulated the author on presenting such an interesting paper and on his skill as a photographer and model-maker.

The meeting terminated at 9.30 p.m., after which light refreshments were served.

Dinner and Dance

The fifth Dinner and Dance of the Section was held on Saturday, 9th December 1961, at the Grosvenor Restaurant, Glasgow, at 6 p.m.

Chairman of the Section, Mr. J. W. Bull, and Mrs. Bull, received the 190 members and guests.

After the Dinner, dancing continued throughout the evening when prizes and novelties were distributed, and a most enjoyable time was spent by all those present.

At the Annual Dinner of the South Wales Section. From l. to r. Mr. David Skae (Vice-President) Vice-Chairman of the Section, Mr. B. P. Ingamells, C.B.E. (Chairman of Council), Mr. F. R. Hartley (Chairman of the Section), Mr. J. Leighton Seager, Chairman, Bristol Channel Shipowners' Association, Mr. J. Stuart Robinson, M.A. (Secretary of the Institute) (standing at back) and Mr. J. Selwyn Caswell, M.Sc. President, The South Wales Institute of Engineers

South Wales

Annual Dinner

The Annual Dinner of the South Wales Section was held on Friday, 10th November 1961 at the Royal Hotel, Cardiff.

Mr. F. R. Hartley (Chairman of the Section) was in the Chair and among the 145 members and guests who attended were Mr. B. P. Ingamells, C.B.E. (Chairman of Council), Mr. J. Stuart Robinson, M.A. (Secretary), Mr. David Skae (Vice-President) Vice-Chairman of the South Wales Section, Mr. J. R. Vickery (Vice-Chairman of the West of England Section), Mr. J. Selwyn Caswell, M.Sc., President of the South Wales Institute of Engineers and Mr. J. Leighton Seager, Chairman of the Bristol Channel Shipowners' Association.

The Toast "The Shipping Industry" was proposed by Mr. Selwyn Caswell and replied to by Mr. Leighton Seager.

Chairman of Council, Mr. B. P. Ingamells, C.B.E., proposed the Toast "The South Wales Section of the Institute of Marine Engineers" and presented the apologies of the President for his inability to be present.

Mr. F. R. Hartley (Chairman of the South Wales Section) responded and in conclusion thanked the members of the Section for their support during his year of Office.

West of England Section

Dinner and Dance

The second Annual Dinner and Dance of the West of England Section was held at the Royal Hotel, Bristol, on Saturday, 28th October 1961.

The 120 members and guests were received by the Section's Chairman, Captain W. R. Stewart, R.N., and Mrs. Stewart, at a reception prior to the Dinner. The principal guests were the Chairman of the Council, Mr. B. P. Ingamells, C.B.E., and Mrs. Ingamells, the Chairman of the Devon and Cornwall Section, Mr. W. E. B. Dainton, and Mrs. Dainton, and also the Chairman of the South Wales Section, Mr. F. R. Hartley, and Mrs. Hartley.

Following the Loyal Toasts the Chairman welcomed the principal guests. He then paid tribute to Mr. Ingamells for his share during his eight years as member of Council, in forming the vigorous policy of the Institute resulting in its present very healthy state. The Chairman said that before proposing the toast of Ladies and Guests he would like to say that he would not have had the privilege of presiding as Chairman had it not been for the sad loss which the Section suffered earlier in the year by the very sudden death of Mr. John. Mr. John had been Chairman for a number of years and in addition to his great interest in the activities of the Institute he was a very warm hearted man and he felt sure that members would remember him with gratitude.

The Chairman then proposed the toast of Ladies and Guests.

Mr. Ingamells, replying on behalf of the Ladies and Guests, thanked the Chairman for his address of welcome and said that it gave both Mrs. Ingamells and himself great pleasure in accepting his invitation to attend the Section's Second Annual Dinner and Dance. He congratulated the Section for organizing a function in which the ladies could take part, and was pleased to note that 120 people had assembled for the occasion, but said that he would like to see this figure doubled on the next occasion. In conclusion, Mr. Ingamells said that the West of England Section was inaugurated at a meeting held at the Royal Hotel, Bristol, in 1954 and that the Section was now almost seven years old. He was very pleased to learn that the number of registered members had increased from 80 to 230 during that time and wished the Section continued progress in the future.

Dancing to the orchestra of Arthur Alexander which included a number of novelty dances, followed the Dinner, until hands were joined at midnight for Auld Lang Syne.

West of England Section

At the Annual Dinner Dance at Bristol, from l. to r. Mrs. Ingamells, Mr. B. P. Ingamells, C.B.E. (Chairman of Council), Capt. W. R. Stewart, R.N. (Chairman of the Section) and Mrs. Stewart

Ordinary Meeting

An Ordinary Meeting of the West of England Section was held at Smith's Assembly Rooms, Bath, on Monday, 13th November at 7.30 p.m. Mr. J. P. Vickery (Vice-Chairman of the Section) presided and there was an audience of thirty-four, including the Local Vice-President, Mr. D. W. Gelling.

In opening the proceedings the Chairman introduced Mr. J. C. G. Hill, who presented a paper entitled "The St. Lawrence Seaway". With the aid of two cine films, Mr. Hill delivered a most interesting lecture on a subject somewhat different in character to that usually presented.

To give members some idea of the history behind the building of the seaway between the Great Lakes and the St. Lawrence River, and also of the problems involved in its construction, Mr. Hill showed the Canadian film entitled "Power and Passage", which was kindly lent to the Section by Mr. N. E. Spencer of Canadian Pacific Railways, Bristol. Mr. Hill then went on to describe in detail many of the points made in the film and concluded by showing his own film made on a voyage of the s.s. *Toronto City* from Avonmouth to Chicago. The photography of Mr. Hill's film was excellent and it gave members a very good idea of the teamwork required by both the deck and engine-room departments of a ship together with the St. Lawrence Seaway crews in the safe handling of a vessel through the various locks.

Eight speakers took part in the discussion which followed, all questions being ably dealt with by the lecturer.

A vote of thanks to the author, proposed by the Chairman, was enthusiastically received. The meeting ended at 9.40 p.m.

General Meeting

A general meeting of the Section was held on Monday, 11th December 1961, at the University of Bristol, at 7.30 p.m. Mr. J. P. Vickery (Vice-Chairman of the Section) presided over the meeting which was attended by thirty-two members and guests including the Local Vice-President, Mr. D. W. Gelling.

The Chairman opened proceedings by introducing Mr. R. M. Duggan, M.A. and Mr. A. T. O. Howell, who presented their paper entitled "The Trials and Operation of the Gas Turbine Ship Auris". The paper which was divided into three parts, was illustrated by numerous lantern slides and a short cine film, and recorded the extensive basin and sea trials and subsequent commercial service of the first British ocean-going gas turbine merchant ship.

Fourteen speakers took part in the discussion which followed, and all questions were ably dealt with by the authors.

A vote of thanks to the authors, proposed by the Chairman was warmly received. The meeting ended at 9.30 p.m.

Election of Members

Elected on the 18th December 1961

MEMBERS

Cedric Barclay, M.Sc.
Cecil Charles John French, M.Sc.(Eng.), London
Bengt Gunnar Johnsson
George Dwight Kingsley, Jr., Lieut., U.S.N.
James Sherwood Knox
Henry Charles Lockhart
Kenneth George Marlow
Ronald William Ernest Martin, Cdr., V.R.D., R.N.R.
John Edward Townson Middleditch, Lieut. Cdr., R.N.
Brian Wyatt Millington, B.Sc.(Eng.), London
Lars Vilhelm Nordstrom

M. V. Philippose
Douglas W. Ruddick
Alexander Cowie Smith
Leslie Charles Stevens, Eng. Lieut., R.N.
Andrew Graham Taylor

ASSOCIATE MEMBERS
Henry A'bruzzese
Derek Ayre
Douglas John Bowen
Alexander Brodie
Ved Sharan Chhabra
Vincent Derek Young Cochran
Robert William Currie
John Michael Ford, B.Sc.
Bjorn Hans Olof Friden
Ian Gardner Hall
John Joseph Hutcheson
Louis Jordan
James Humphrey Lapsley
Franciscus Johannes Leijgraaff
Leo Patrick McGahan
Patrick William John McMenamie
Pullat Sethu Madhavan
Alan William Overington
Kenneth Kay Paterson
Anthony John Vaughan Peach
Arnold Rycroft
Edward Reid Shand
William Gordon Southern
Otto Staedeli
Lars Erik Magnus Tengberg
Robert Turner
William Wait
Arthur White

ASSOCIATES
Edmund Marciano Beckford
Neil Grant Mullett
Terence James Pope
Joseph Robinson, Lieut., R.N.V.R.
Sidney Sharkey
Ram Kumar Singh, Cd. Eng., I.N.

GRADUATES
John Addison
Hassan Masood Ansari, Lieut., P.N.
David Bailey
James Ball
Joseph Brookes
Allan Dale Craig
John Wallace Driscoll
Guillermo Fornes
David Michael Haywood
Brendan Aloysius McCann
Robert Morrison McIntosh
K. R. L. Perera, Lieut., Royal Ceylon Navy
Walter Gibson Scott
Arthur Eric Train

STUDENTS
Godwin Akpevwiehor
John Alder
David Keith Arnold
Richard Stephen Barnes
William Henry Barnett
Haralambos A. Baroutakis
Michael A. Baroutakis
Michael John Barry
Paul Kenneth Bentley
Anthony Paul Bray
Roland Broadbent
Juan Glyn Burns
Desmond Butler
David Geoffrey Challinor
John Alfred Chambers
David Ronald Clarke
James Alastair Crombie
Carl Dalton
Christopher Ivor Davies
John Ironside Dawson
Peter David Dombey
Malcolm Leslie Dunley
Peter Allyn Antony Edwards
Roger England
Ronald Manson Gale
Raymond Gilbert
Anthony Michael Green
Denis Griffiths
Hans Elenius Hansen-Tangen
Alan Hardy
Lewis Fingland Harrison
John Wilson Henderson
Peter Glynn Hughes
Gregory Francis James
Geoffrey Robert Jones
Richard Keats
Peter Kennedy
Brian George King
Anthony Peter Lancaster
Harry Lyons
John Sibbald McCormick
William McGhee
Hugh Muir Meldrum
Amal Mitra
Patrick Lewis Moore
John Eric Moss
Donald Malcolm Munro
John Frederick O'Connor
John Hadlow Ogle
Arthur George Parrott
Peter John Riley
Michael Raymond Rogers
John Arthur Rooker
Christopher Harrison Shaw
Michael Charles Squibb
Malcolm Harold Stephens
Michael Thomas
Stewart Topping
Brian Trevor
David Tucker
Brian Antony Underwood
Christopher Anthony Vye
William Arthur Wanstall
Malcolm George Weaver
Keith Whitehall
Humphrey Martin Wills
William Robert Wilson
Kenneth Donald Winhall
Erik Muir Ziegler

PROBATIONER STUDENTS
Sunday Udo Akpan
Roy Andrew
David Kenneth Anson
Peter Douglas Astles
John Gordon Atkinson
Thomas Henry Bate
Hugh Alexander Bates
John William Berry
David William Bethell
Leslie Patrick Beckett
John Martin Benn
Ewan Montague Berkley
Ian Gerald Bird
Robert H. B. Birt
Ian Faid Blair
Bryan John Blake

William Blake
Frank Edward Bock
John Leonard Buxton
Anthony William Byrne
Donald Campbell
John Campbell
Stuart Campbell
Paul Anthony Chapleo
Edward Clark
Kenneth Macdonald Clark
Colin Clegg
Bryan Robin Clydesdale
Michael John Connolly
Charles Barry Connoly
John Reginald Cooper
Richard Jackson Coverdale
Thomas David Critchlow
David Russell Crowther
Barry John Dean
Leslie William Douthwaite
Clifford Graham Eagle
David Stewart Edgar
David John Eldridge
Michael John Elliott
John Woods Ferguson
Bryan Robert Flower-Ellis
Ian David Forrest
Rodney Lee Foster
John Alfred George
Peter Bruce George
Robert Alexander Goble
Christopher Goodman
Iain Donald Grahame
John Brian Gray
John Fraser Gray
James Albert Green
Michael Green
Ian Hall
James Francis Hall
Keith William Hall
Ernest Roy Hanrahan
Jeffrey Hardy
Peter William Hawkins
Alan Shaw Hendry
Henshaw, D.
Hennessy, J. J.
Frederick Richard Hibberd
Stuart Leslie Hockenhull
Anthony Thomas Hogan
George Kenneth Hooson
David Leonard Howarth
Paul Hudson
Terence Thomas Hudson
George Hunt
James Hunter
Jack Walker Hynes
Robert Stevenson Jackson
George William Jamieson
Anthony Michael Johnson
Peter Jones
Alistair Kennedy Joynes
David Robert Kay
Allan Melville Kennan
Abdul Malik Yassin Khan
David John King
Stuart Kneen
David Anthony Reginald Knowles-Leak
Kenneth Gray Lee
Roger Ernest Leeson
David McFarlane Leitch
Eric Leslie Linge
John David Little
Ian Hugh Deans McAuslan
Edmund Brian Campbell McCallin
Ian Reid McDade
Laurence John McDonald
John Baird McIntosh
John Cunningham Marchbank McKerrell
Neil D. Mackintosh
Robert Urquhart McLean
Alexander McMahon
Michael Anthony Maddock
Robert Madrell
David Holland Mann
Philip Arnold Mann
Andrew Nicholas Martyn
Philip Longton Mawdsley
Alwyn Barrie Mayer
Eugene Patrick Mehigan
Brian Milton
David Ernest Morrill
Duncan William Morse
Peter Frank Moss
David Newton
James Christopher Nicholls
Eric Northey
Michael Douglas Richard Oldfield
John Stanley Owen
Keith Robert Parnell
David Anthony Parsons
David William Paul
John Peers
Donald Martin Henry Perham
David Pickering
Michael Powalski
John Laing Rae
Ian James Rawlinson
John Redman
William Munro Reid
John Alexander Ridgway
John Keith Riley
John Arthur Robertson
Peter Rossiter
David Rowbotham
Peter Leonard William Russell
John Philip Sidney Rylance
Clifford Sawle
Alastair Forbes Scott
Ian Craig Scott
W. Gordon Sellars
Philip John Richard Selwyn-Smith
Daniel Sherwin
Richard William Stanley
James Nicol Stark
Philip Julian Steer
Bruce Innes Steven
Allan Stewart
Robert Stokell
James Barrie Stopforth
Richard Nelson Taylor
John Kenneth Tomlins
John Travis
Carl Eric Tune
Geoffrey Albert Turner
Peter Turner
Wilfred George Turner
John Goodwin Victory
Arthur Walker
Ian Edgar Maynard Walker
William Wallace
Christopher John Walter
Norman James Wardil
David Alexander Webb
Robert John White
Lawrence Whitehead
Richard Vessey Whittaker
Philip Anthony Wilkinson
Roger Williams

John Frederick Wilsdon
John Radcliffe Wood
George Worrall
Peter Barry York

TRANSFERRED FROM ASSOCIATE MEMBER TO MEMBER
Keith Stenson Harvey
Bernard Valentine Hill
Keith Alec Holes, B.Sc.(Eng.)
Kenneth William Moore, Lieut., R.C.N.
Alan James Scott
James Stevenson

TRANSFERRED FROM ASSOCIATE TO MEMBER
James Douglas Bye
Thomas James Watt

TRANSFERRED FROM ASSOCIATE TO ASSOCIATE MEMBER
Frank Vincent Edwards
Thomas Frederick Norman Mascall, Lieut., R.C.N.

TRANSFERRED FROM GRADUATE TO ASSOCIATE MEMBER
William Christopher Baldry
William Arthur Currie
Robert Leitch Logan
David McGlashan
Neville James Matthew
Sennen Anthony Perera
Prem Prakash, Lieut., I.N.
John Edmund Talbot

TRANSFERRED FROM GRADUATE TO ASSOCIATE
Walter Glyn Rhys

TRANSFERRED FROM STUDENT TO ASSOCIATE MEMBER
David John Heaslip

TRANSFERRED FROM STUDENT TO GRADUATE
John Oliver Brinkley
Richard Quirk
John Colin Taylor

TRANSFERRED FROM PROBATIONER STUDENT TO GRADUATE
John Sydney Michael Sutton

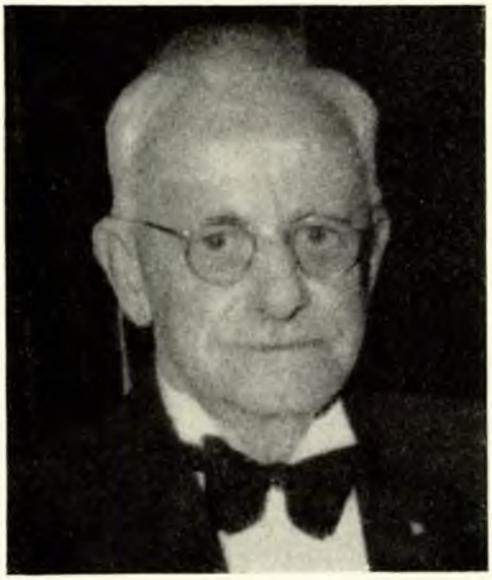
TRANSFERRED FROM PROBATIONER STUDENT TO STUDENT
Alan Vernon Albutt
David Robert Burden
Michael Byrne Diggle
David Frederick Fletcher
Donald John Macdonald
Keith Wilson

OBITUARY

Idwal William Jones Evans (Member 3074), Local Vice-President for the Institute at Cape Town died on 21st August 1961 aged 70. Mr. Jones Evans served an apprenticeship with the Great Western Railway Co. Ltd. at Swindon and afterwards was at sea for three years, when he took a Second Class Certificate, and then his First Class Board of Trade Steam and Motor Certificate.

During World War One he served in transports carrying troops to France and later in s.s. *Saxon* carrying troops to the Dardanelles. From 1918-20 he served in the *Ipu* as chief engineer in East Africa. In 1921 he was appointed to the *Arundel Castle* and then to the m.v. *Carnarvon Castle* in 1925.

Early in 1928 he went out to South Africa to the Concordia copper mines in Namaqualand as chief engineer. These were closed in 1931. During this period Mr. Jones Evans married and brought his wife out from Wales.



He started in 1931 as a consulting engineer in Cape Town and later as an independent marine surveyor. He acted for the American Bureau of Shipping, Bureau Veritas, Det Norske Veritas, Lloyd's Register of Shipping, Registro Italiano Navale, Nippon Kaiji Kyokai and Germanischer Lloyd. He died while carrying out a survey on t.s.s. *African Lighting*.

Mr. Jones Evans had been Local Vice-President at Cape Town since 1949 and had served as Chairman of the Cape Town Section in 1955. He had been elected an Associate Member in 1915 and was transferred to full Membership in 1918. Mr. Jones Evans was an ex-President of the Cambrian Society at Cape Town.

Edwin Percy Bamford (Member 8098) was born in London on 26th July 1885. He served his apprenticeship first with Messrs. David Hart and Co. (between 1900-04) and for the following two years with the Thames Iron Works. In 1906 he sailed as a junior engineer with a frozen meat company, mainly on the New Zealand run. In 1914 Mr. Bamford began a long association with Shell Mex and Company by joining the Anglo-Saxon Petroleum Co. Ltd. (as it was then) and sailed for the next three years between Hong Kong and Singapore. Later, while in the Mediterranean "feeding" the *Queen Elizabeth* and other large ships his tanker was torpedoed. The ship was abandoned but later Mr. Bamford realized she was not going to sink, and calling for volunteers, the team of salvagers succeeded in beaching the vessel on Crete. After a few urgent repairs the tanker proceeded to Malta for final repairs. For his part in this operation, Mr. Bamford was awarded Lloyd's Silver Medal. Having obtained his First Class Board of Trade Certificate, he returned to Liverpool in 1920 to assist the superintendent engineer there, and was later appointed a superintendent engineer himself. He served in this capacity until the Second World War, when he was seconded to the Ministry of War Transport. In his Government post, Mr. Bamford was responsible for the speedy turnround of all tankers coming to Merseyside. By the end of the war his retirement from Shell Mex became due and, although Londoners, he and his wife decided to settle in Cheshire, having a great love of the Wirral, and many friends there.

Mr. Bamford became a Member of the Institute in 1936. He died on 14th October 1961.

James Leo Bradley (Member 17699) who was born on 6th October 1888 died recently in his 73rd year. He served his apprenticeship with the City of Dublin Steam Packet Company, Liverpool between 1906-11, and went to sea with T. and J. Harrison Ltd. from 1911-14. In December 1914 he obtained his First Class Board of Trade Steam Certificate and returned to sea with the Cunard Line, serving in various grades from fifth to second engineer until 1919, when he continued his service with Cunard as junior fourth engineer aboard the R.M.S. *Imperator*. Mr. Bradley thereafter served with the R. D. Houston Line where he was promoted to chief engineer in 1933, and with the Clan Line and associated companies, also in the capacity of chief engineer.

He retired from active service in July 1956, in which month Mr. Bradley was elected to full Membership of the Institute.

Howard Eric Crompton (Associate 24025) died on 13th November 1961, only two months after his election to Associateship of the Institute. Born on 8th April 1912, Mr. Crompton was educated to Higher School Certificate standard and had attended a full-time degree course in mechanical engineering at The Northampton Engineering College for five years. In 1938 he joined Henry Hughes and Son Ltd (now Kelvin and Hughes Ltd.) of Barkingside, Essex, the manufacturers of navigational equipment for shipping and aviation. For two years he was engaged as a junior production engineer on the manufacture of marine navigational equipment and was then promoted senior production engineer. After a year in that position, Mr. Crompton was appointed senior design engineer, a post he held for the next ten years until his promotion to the post of chief design engineer of Kelvin and Hughes Ltd. At Kelvin and Hughes he was responsible for the design, development and prototype testing of navigational equipment for both marine and aviation applications and also for the production of test equipment for special processes. He was directly responsible to the chief development engineer of the company for a team of design engineers and draughtsmen.

Howard Crompton was the elder son of the late Frank Crompton and was a director of Blundell and Crompton Ltd., the ship repairers and engineers of West India Dock Road, Millwall. He will be sadly missed by his colleagues.

George Briggs Keppie (Member 7161) was born on 6th September 1895. His apprenticeship he served with Messrs. Hay and Robertson, Dunfermline. After serving in the Royal Navy for 3½ years during the First World War, Mr. Keppie joined the British India Steam Navigation Co. Ltd. at the age of 23, and thus began a career which was to take him right through the Second World War up to 1950, in the service of that company. His first appointment was to s.s. *Chupra.* He then served in turn as fourth, third and second engineer and was appointed chief engineer in March 1936, continuing to serve in that capacity until 26th November 1950 when he retired from the company. Mr. Keppie joined s.s. *Vasna* in January 1938 and served continually in the vessel, which acted as a hospital ship throughout the war, mostly in Eastern waters, until November 1945. On his return from leave in June 1947, he served in s.s *Khandalla, Varsova, Canara, Vasna, Dara* and *Garbeta* until his retirement. He held a First Class Board of Trade Certificate. Mr. Keppie joined the Institute in 1932 as a full Member. He died on 29th July 1961.

Harry Rainford (Member 7867) was born on 6th September 1893. He was indentured with Messrs. Swallow Davis and Co., St. Helens between 1908-11 and with Messrs. G. W. Strafford and Co., Liverpool from 1912-15.

Mr. Rainford then served at sea for 11 years with an interval of two years from 1919-21 as works manager for Messrs. Pearson and Son, Dublin. In 1928 he joined the Clan Line and served in 1935 as third engineer in s.s. *Clan Macindoe,* in 1939 with Messrs. Clan Line Steamers and in May 1945 was appointed superintendent engineer with the Clan Line at Bombay.

He became a Member of the Institute on 13th May 1945. Mr. Rainford died on 7th November 1961.