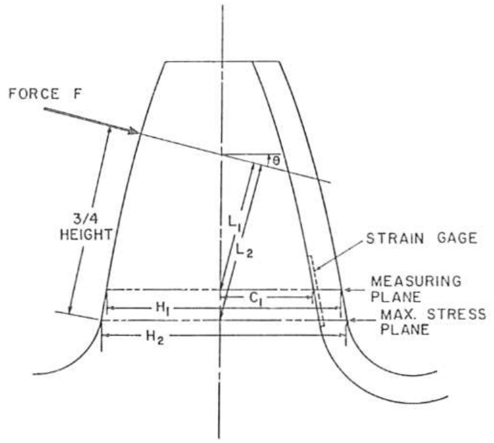

Fig. 8 Relation of Strain Gage to Root Fillet

With reference to Fig. 8 it can be seen that the measuring plane is above the maximum-stress plane so that the normal compressive stress is greater on the measuring plane than the maximum-stress plane. No correction has been made for the effect of reduced thickness at the machined recess in calculating the normal compressive stress and bending stress.

The position of the load line when the maximum gage stress occurs has been determined to be at approximately $^3/_4$ of the tooth height. When this is known, plus the geometry of the tooth and the gage position, the relative bending stresses can be determined. The ratio of the combinations of the bending and normal compressive stresses at the maximum-stress plane and at the gage in the measuring plane is the factor by which the gage stress can be multiplied to supply the tensile stress at the root fillet.

Two cases are possible, when the load is on the side of the tooth opposite the gage and when the load is on the gage side of the tooth. When the load is on the side of the tooth opposite the gage, astern operation, the following applies (see Fig. 8):

The bending stress at the gage center, in the measuring plane

$$\sigma_{B1} = \frac{-12FL_1C_1}{H_1^3}$$

and the normal compressive stress, at gage center

$$\sigma_{N1} = \frac{-F \sin \theta}{H_1}$$

For the point at the beginning of the root fillet in the maximum-stress plane on the load side of the tooth the bending stress

$$\sigma_{B2} = \frac{6FL_2}{H_2^2}$$

and the normal compressive stress

$$\sigma_{N2} = \frac{-F \sin \theta}{H_2}$$

The total stress at the gage

$$\sigma_G = \sigma_{B1} + \sigma_{N1}$$

The maximum tensile stress on the load side of the tooth

$$\sigma_T = \sigma_{B2} + \sigma_{N2}$$

The factor to change maximum gage stress to maximum tensile stress is σ_T/σ_G where

$$\frac{\sigma_T}{\sigma_G} = \frac{\sigma_{B2} + \sigma_{N2}}{\sigma_{B1} + \sigma_{N1}}$$

With the substitution of expressions for the bending and normal stresses, the factor reduces to

$$\frac{\sigma_T}{\sigma_G} = -\left(\frac{H_1}{H_2}\right)^2 \frac{6L_2 - H_2 \sin \theta}{12L_1 \dfrac{C_1}{H_1} + H_1 \sin \theta}$$

When the load is on the gage side of the tooth, ahead operation, the foregoing applies with the exception that σ_{B1} is positive and σ_{B2} is on the gage side of the tooth. The factor reduces to

$$\frac{\sigma_T}{\sigma_G} = \left(\frac{H_1}{H_2}\right)^2 \frac{6L_2 - H_2 \sin \theta}{12L_1 \dfrac{C_1}{H_1} - H_1 \sin \theta}$$

For this particular test the maximum gage stress occurs when the load is approximately $^3/_4$ the height of the tooth. With this and the geometry of the tooth and gage location the factors to change gage stress to tensile stress at the root fillet were calculated to be —1.25 for astern operation and 1.54 for ahead operation.

Discussion

M. S. Berg.[3] This experimental tooth-stress test is a pioneer effort which was long overdue in the measurement of tooth stresses of full-size marine gears. The test limited in its scope forms the basis for future work which will be of great importance to the gear designer. The effects of helix-angle variation, tooth spacing, and many other factors can now be evaluated accurately in the laboratory in a reasonable time.

It is presumed that the state of the art for installing strain gages limits the tooth size on which such gages can be installed and that the method would not be practicable for determining tooth stress on production units owing to cost and time consumed in such testing. Since the authors mention that the time-honored visual means for determining tooth contact showed a high degree of uniformity, it would seem that a more accurate means for obtaining tooth contact should be developed.

The table does not indicate the effects which would be expected from torsional twist. It may be that the effect of torsional twist is masked by greater stresses from other causes.

It would be of interest to know the helix-angle mismating determined by measurements and the correlation of such measurements with the stress patterns obtained.

Joseph Cacciola.[4] Congratulations are in order for this concise and able presentation. The derived data indicate load concentrations in operation which have long been suspected in wide-face marine gears although not normally to the extent shown in these studies. The need for further investigations of this type to allow evaluation of alteration in design or helix-angle modification is well justified. A disadvantage of the described method lies in the necessity for machining a recess in the tooth surface for mounting the strain gage. Similar investigations are being conducted at the Naval Boiler and Turbine Laboratory to develop techniques for application of strain gages without modification to helical gear teeth. This has been accomplished using curved resistance gages which are cemented directly upon the gear tooth in the fillet area. Precise location is virtually

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[4] U. S. Naval Boiler and Turbine Laboratory, Naval Base, Philadelphia, Pa.

impossible under these conditions. Accordingly, a calibrating device was designed to impose static load of known magnitude upon selected areas of the instrumented teeth. By applying load between two parallel and flat jaw faces spanning a selected number of teeth, contact may be made extending from the tooth tip diagonally across the tooth in virtual duplication of actual contact occurring between mating gear and pinion. Calibration is accomplished by shifting the position of the load applier across the tooth face until the maximum gage output is determined for a given load. Similar calibrations of other gages then permits a determination of relative load distribution. Actual calibration of a group of gages mounted on a double helical pinion has shown an appreciable variation in resistance change per unit load for similarly mounted gages. Limited test operation has now demonstrated this manner of gage application and calibration to be practical. A similar calibration procedure is suggested for the test discussed by the authors.

In Table 1 of the paper, gages have indicated a serious concentration of load for the upper gear, aft helix and the lower gear, forward helix for all ahead runs. It is puzzling that maldistribution of load of this severity should not be evident in visual examination. Our experience has shown fax-film enlargements to be helpful in detecting nonuniformity of load distribution within the face width and in the involute profile through removal of initial tool markings through polishing action or by the appearance of distress markings such as pits, radial scuff marks, or other indication. Copper plating with electrical brush deposition of a layer of copper less than 0.0001 in. thick also has been helpful in showing areas of distress. Although these inspections cannot yield data obtained by strain gage, their application in the described tests should provide some correlation to test data which should prove valuable in future service examinations wherein interpretation of load distribution can only be made by surface appearance.

L. J. Collins.[5] The method employed by the authors in an effort to measure the root stress in gear teeth is of considerable interest and the fact that they made an effort to familiarize the industry with the method is greatly appreciated.

Although we have studied the data presented in Table 1, it does not seem to be in order to discuss these data since the primary purpose of the paper was to present a description of a measuring technique.

The authors referred to laboratory tests being conducted at the present time. If data are made available at the completion of these tests, the degree of accuracy of the mating-gear elements should be recorded. Errors in helix angle, tooth spacing, and alignment are all variables and will affect the value of the conclusions reached.

In all probability the method of measurement outlined in the paper would not be allowed on a production unit. For this reason then, physical measurements of the test pieces must be made accurately and the effect of all variables evaluated as accurately as possible. If this is done, and if the physical measurements of a production piece are known, then the probable stresses to which the production piece will be subjected can be estimated.

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H. Engvall.[6] The paper is quite timely, dealing as it does with a subject that in the last several years has become very important; namely, the bending stresses in gear teeth. The need of the Navy for compact lightweight gear reductions and the construction of large freighters and supertankers built to operate at high speeds, made it necessary to design gear reductions capable of transmitting the required power day in and day out without failure. Naturally, as the power increased, the sizes of the gears increased and so did the problems connected with their design. Because of weight and space, considerations which affect both manufacturing and ship installations, it became necessary to increase gear-tooth loadings as far as possible without affecting the dependability of the gearing. Among the steps taken that made it possible to do this successfully were:

1 Increased accuracy in gear hobbing.
2 Improved tooth form.
3 Improved tooth finish.
4 The use of better material.
5 Realistic design of the gear elements.

In the past, gear troubles were confined mostly to breakdown of tooth surfaces due to pitting, scuffing, etc., but as these troubles were overcome by improved manufacturing techniques and gear loadings were increased, tooth breakage began to show up and it was then recognized that new design standards were required.

The bending stresses in gear teeth naturally increase directly with tooth loadings and the tooth loadings per inch of face, for a given K-factor, increase directly with the diameter of the pinion. As the gears designed today not only must have larger dimensions because of the increased power rating but also must be designed for higher K-factors, it is obvious why the tooth-bending stresses have become a very important design consideration. The only way to reduce the bending stresses in a given design is to increase the size of the gear teeth because the stresses roughly vary directly with the size of the teeth.

In the past our knowledge of these stresses was based on the result of photoelastic studies but during the past several years extended laboratory tests, such as the torque test referred to in this paper and actual installations aboard ship of highly loaded gears, have shed enough light upon the subject to permit us to design gears successfully that meet today's requirements.

The test described in this paper must be looked upon as the first step toward acquiring new and perhaps more fundamental knowledge on this subject and the authors are to be congratulated upon having taken such a chore upon themselves.

Authors' Closure

Mr. Berg raises an interesting point regarding correlation between stress patterns and helix-angle mismating. The helix angles of the test gears were matched so that the only expected stress variation was that due to torsion of the pinion body.

The authors are gratified that the Naval Boiler and Turbine Laboratory is making further investigation into the application of strain gages to gear teeth. It would be helpful indeed if a method could be developed that would give positive measure of tooth load distribution in a service set of gears.

The authors hope that continuation of the present series of tests can be carried to a conclusion that will define the magnitude of all variables which affect tooth load distribution.

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