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# SHOT PEENED GEARS AS EVALUATED BY SINGLE TOOTH FATIGUE TESTS

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Shot peening improves the fatigue strength of gear teeth. There is generally no argument over that statement. But how much of an improvement can actually be made in the load carrying capacity? Many gears have been run in rotating tests showing that the life at a constant load is increased or that higher loads can be carried without failure. These show, in a general way, that the bending strength of the teeth is increased by shot peening.

However, other types of gear failure - such as pitting, scuffing, or wear - often tend to confuse the results when tests are run at high loads or extended times. This makes the quantitative evaluation of shot peening quite difficult with rotating tests. Gears can fail in so many ways that it is often desirable to isolate the type of failure under study by eliminating the possibility of other types of failure.

The single tooth bending fatigue test does just that - isolates the type of failure. Surface deterioration failures cannot occur because there is no relative motion between mating surfaces. The only type of failure that can normally occur is bending fatigue failure at the root fillet.

What is the principle of the single tooth test? Consider a gear as a wheel with a number of carefully shaped cantilever beams projecting from its periphery. When we want to determine the strength of a cantilever beam projecting from a part, we generally hold the part stationary and apply a load to the outer portion of the beam until failure occurs. This - when done with the cantilever beams of a gear - is single tooth testing.

The principle of the test is very simple. Its operation is also simple. When a single tooth fatigue test is run on a gear, one tooth is loaded with a certain alternating load. If no failure occurs, the test is stopped after a certain number of cycles, usually five or ten million. After the test the gear is removed from the fixture, rotated two or more teeth, and replaced in the fixture. It is thus indexed so that another tooth is in position for test. This tooth is then loaded either above or below the load of the previous test, depending upon the earlier results. In this manner many teeth on the same gear may be tested. If desired, a good idea of the endurance limit may be obtained.

A gear containing a single metallurgical change may then be tested similarly. Whether the variable be in material or processing, the results may be compared directly with those of other gears tested, providing no other variables are present. For comparative purposes it is not necessary to know the theoretical bending stresses in the root fillet, although this information is useful for a better understanding of the results.

Interpretation of results of any comparative test can be extremely difficult if evaluation of more than one variable at a time is attempted. Suppose the object of a test series is to evaluate the effect of a certain shot peening procedure on gears. If the gears are chosen at random from different steels or even different heats of the same steel, heat treated differently or even at different times, how can an intelligent analysis be made of the effect of shot peening? How much of the change can be attributed to the steel variation? How much to the difference in heat treatment? How much to the shot peening? Considerable guesswork is involved. Yet this type of "analysis" is frequently done.

A much more logical way of attacking the problem of evaluation is to make the test as simple as possible. Choose the test conditions so that the only variable is the one being tested - shot peening. Make a group of identical gears - same bar of steel, forged together, machined consecutively, heat treated together - as similar as is commercially possible. Then select at random part of this group of gears and shot peen them with the desired procedure. After the two groups have been tested with the single tooth fatigue test, the results of each group may be lumped together to evaluate the performance of the group as a whole or the gears may be considered individually since separate endurance limits may be obtained. In this way the change in bending fatigue strength due solely to shot peening may be accurately measured.

It may be asked, "Why use the single tooth test if it does not duplicate the meshing action of a pair of gears?" There are several reasons why this test is suitable for use, because it:

1. Eliminates test machine variables - Wear or failure of shafts, splines, bearings, and other parts of rotating gear tests frequently tend to confuse the test results. In the single tooth test the test tooth receives the load directly. The fixture can be rigidly designed to prevent extraneous failure or damage.

2. Eliminates gear variables - Dimensional variations between pairs of rotating gears may tend to overshadow metallurgical variations. The effect of pitch line runout, tooth spacing, and involute profile errors are eliminated since contact is made in the same position at all times.
3. Uses simple equipment - Standard fatigue testing machines of several different types may be used although special machines are sometimes employed. The constant load type is preferable for this type of testing. Since these machines usually have automatic cutoffs, the tests may be run continuously with the machine stopping upon tooth failure. For spur gears the fixtures are not complex and are easily dismantled for changing the test gear.
4. Permits measurement of bending stress - If the gear teeth are large enough it is relatively easy to measure bending stresses in the root fillet when the test is operating. SR-4 strain gages can be located wherever desired and the operating stresses measured with suitable equipment. These stresses can be calibrated with the test loads as determined by the machine settings so that the actual bending stress is known for each machine setting.
5. Eliminates undesired failures - Progressive surface damage

due to pitting, wear, or scuffing is eliminated since no relative motion occurs against the test tooth. Only bending fatigue failures occur.

No test is perfect. Each has its limitations. The single tooth test is no exception with certain disadvantages that must be recognized, in that the test:

1. Limits failures to bending - If interest is not in bending failures at the root, the test is not suitable since the failure will always occur at the root fillet. Pitting fatigue may be simulated by rolling tests, and wear or scuffing by sliding tests.
2. Lacks direct correlation with operation - In rotating service gear teeth are not loaded individually. Usually at lease one and a half teeth are in contact at an average time. The tangential load carried by the tooth may be obtained from the test, then calculations may be made in terms of the contact ratio to determine the torque this would represent in service.
3. Requires special fixtures - The test may require special fixturing for each design tested. Complete fixture redesign may be necessary for relatively minor gear design changes. Gears with curved teeth such as helical, spiral bevel, and hypoid gears present special problems in fixture design, and the fixtures may become quite complex.

The foregoing paragraphs are an introduction to the principles and operation of the single tooth test. In common use the test has two primary functions: first, to act as a screening test to compare metallurgical variations of a particular problem gear or, second, to serve as a research tool for investigating the factors affecting the bending fatigue strength of gear teeth in general. The two functions are certainly related but can best be summarized by saying that the first is for practical applications, the second for academic purposes.

As an example of its use in a practical situation, field tests of pre-production tractor models containing 14 pitch compound planetary gears showed that the gear was subject to bending fatigue failures. The field tests were time consuming and expensive to run. The many possible variations in design, material, heat treatment, and shot peening treatment made a screening test necessary.

On the basis of the failed field test gears, the design engineers made all the geometrical improvements practical. These included proper crown size and location, also full fillet radii, since it was not possible to change the size or basic tooth design. The balance of the improvement had to be achieved metallurgically or mechanically, as by shot peening. There were 23 teeth in this gear, 7/8 inch face width, 20° pressure angle, standard system.

The test fixture was simple in design. With these relatively small spur gears it was possible to machine an internal gear in a plate with which to hold secure the test gear. A section of the plate was cut away to expose the test tooth for loading. A shaft through the bore of the gear held two arms, one at each end of the shaft, which were fastened to a ram block. A projection from the ram block contacted the test tooth at the pitch line and produced the bending load on the teeth. Since this gear had 23 teeth, it was possible to test as many as ten teeth on each gear to obtain a good idea of the endurance limit under these conditions.

One of the objectives of this test was to evaluate the effect of shot peening. Several gears were forged from the same bar of 4118 steel, machined together, carburized simultaneously for 0.025-0.035 inch case, marquenched in 400 F oil for ten minutes, air cooled, and tempered. All were as identical as commercially possible. Then, some of these gears were shot peened under controlled conditions while the balance were not shot peened. Four gears of each type were tested. Endurance limits for several tests on each gear were found by determining the maximum load at which no failure occurred. Comparative results of endurance limits, in terms of machine load settings, were as follows for the eight separate gears:

| | Nonshot peened | | Shot peened |
|---|---|---|---|
| | 2400 lb | | 3300 lb |
| | 2400 " | | 3100 " |
| | 2300 " | | 2900 " |
| | 2300 " | | 2800 " |
| Avg | 2350 lb | Avg | 3025 lb |

Metallographic examination and microhardness traverses at the root fillets of each gear showed that they were very nearly identical metallurgically. The root hardness traverse bands for each type were quite narrow and overlapped. Chemistry and microstructures were identical.

Since all possible mechanical and metallurgical factors were held constant, the one variable introduced - shot peening - must have been responsible for the increase in bending fatigue strength. That increase was in the order of $\frac{3025-2350}{2350} \times 100 = 29$ percent based upon the averages previously mentioned. Gears which had endurance limits at the 2300-2400 pound level failed on the test track while otherwise similar gears, shot peened as done here, ran successfully with no trouble. Shot peening was the difference between success and failure in this gear. It was economically justified and has remained in use. The bending test results were clear cut and decisive.

Other bending fatigue tests were run in a similar manner on a larger gear. This was a transmission gear used in a large crawler tractor, chosen as being representative of gears in this transmission. The gear itself had 24 teeth with a diametral pitch approximately 4.8. The pressure angle was slightly over 25° and the tooth width was approximately 1.4 inches.

Fixturing was similar to that of the previously mentioned planet gear except that the line of contact was chosen midway between the pitch line and the tip of the tooth. The purpose was to weaken the test tooth by applying the load nearer the tip and to correspondingly permit strengthening of the ram tooth.

Four gears were forged from the same billet of TS-8620 steel, and were machined and carburized together to eliminate all possible variables. This was for the purpose of more accurately evaluating the effect of shot peening. The gears were all shot cleaned, then two were picked at random and shot peened.

The results, as measured by endurance limits, were as follows on the four gears tested:

(See next page)

| | Nonshot peened | Shot peened |
|---|---|---|
| | 13,000 lb | 15,500 lb |
| | 12,000 " | 15,000 " |
| Avg | 12,500 lb | 15,250 lb |

Superimposing the shot peening action upon the shot cleaned surfaces resulted in an approximate endurance limit increase of $\frac{15,250 - 12,500}{12,500} \times 100 = 22$ percent. Again, examination revealed that the gears were very nearly identical within the limits of accuracy of the metallurgical tests.

Another single tooth test involved a very large sprocket drive gear from a crawler tractor. Teeth could not be broken out in a massive four square type of machine, although failure sometimes occurred under severe field service. This gear had an O. D. of slightly over 31 inches, with a face width of over 4 inches. The 77 teeth were 2.5 diametral pitch with a 22° pressure angle. It had a short addendum causing the pitch line to be near the tip of the teeth. The gear was a large ring which normally was riveted to a gear carrier, or hub, for tractor installation. The gear was roll forged from 1045 steel, normalized, induction hardened, and tempered.

In order to evaluate the effect of proposed metallurgical variations it was necessary to devise a test that could duplicate field failures in bending fatigue. The final test fixture operated on the principle of torque applied to a shaft which in turn oscillated against the test tooth. The large final drive gear was clamped and braced in a vertical position to the base of the machine. with the test tooth positioned at the bottom. Through a link, a reciprocating slide at the top of the machine oscillated the vertical lever arm fastened to a large shaft running parallel to the base of the machine under the test tooth. Mounted in bearings, the shaft contained a 1/2 inch diameter pin, braced from behind, which contacted the test tooth along the pitch line. It was necessary to machine off part of the adjacent tooth to provide room for reinforcement of the loading pin.

It is usually desirable to obtain the endurance limit as a measure of relative load carrying capacity. However, other considerations may make this impractical. Quantitative measures of strength cannot be obtained with tests of life at a single load. Only trends can be established. However, it was not practical to obtain endurance limits on these gears since they operate quite slowly in service and each tooth needs to withstand relatively few cycles at maximum load. Also, because of the slow speed of the testing machine, the tests necessary would be too time consuming. Consequently, the tests were run at an arbitrarily selected high load.

Shot peening was investigated on these large gears also. In many cases both shot-peened and nonshot-peened teeth on the same gear were tested. This was done by masking certain teeth and peening the balance. In this way the variables were cut to a minimum. Some representative comparisons in life at a tangential alternating load of 84,800 pounds were as follows:

(See next page)

| Gear | Cycles to Failure | |
|---|---|---|
| | Nonshot peened | Shot peened |
| A | 73,000 | 715,000 |
| | 66,000 | 385,000 |
| | 51,000 | 233,000 |
| | 50,000 | |
| | 49,000 | |
| | 40,000 | |
| B | 88,000 | 241,000 |
| | 80,000 | 201,000 |
| | 77,000 | 170,000 |
| | 76,000 | 143,000 |
| C | 57,000 | 116,000 |
| | 47,000 | 95,000 |
| | 35,000 | 89,000 |
| D | 88,000 | 192,000 |
| | 77,000 | 155,000 |
| | 53,000 | 106,000 |

These tests show increase in life due to shot peening although it is difficult to evaluate quantitatively the degree of improvement.

## Summary

The single tooth fatigue test is valuable in evaluating the bending strength of spur gear teeth. It isolates the type of failure to that desired without the complicating effect of other types of failure. It is ideal for evaluating the role of shot peening in increasing the strength. Variables in the shot peening process can also be readily evaluated so that the most economical combination of shot size, arc height, and coverage may be determined. The future will undoubtedly show increasing use of this test for the testing of bending fatigue strength of gear teeth.

## APPENDIX

The chemical analyses of the gears referred to are as follows:

| | Planet Gear | Transmission Gear | Final Drive Gear (Range) |
|---|---|---|---|
| Carbon | 0.23 | 0.22 | 0.43-0.50 |
| Manganese | 0.83 | 0.90 | 0.80-1.00 |
| Silicon (range) | 0.20-0.35 | 0.20-0.35 | 0.15-0.30 |
| Sulfur | 0.013 | 0.027 | 0.05 Max |
| Phosphorus | <0.04 | <0.04 | 0.04 Max |
| Nickel | 0.11 | 0.46 | - |
| Chromium | 0.55 | 0.72 | - |
| Molybdenum | 0.10 | 0.10 | - |
| Steel type | 4118 | TS-8620 | C-1046 (Mod) |

Pertinent shot peening data is as follows:

| | Planet Gear | Transmission Gear | Final Drive Gear |
|---|---|---|---|
| SAE shot size | S 110 | S 230 | 230 |
| Shot type | Steel | Chilled iron | Chilled iron |
| Wheel size, inches | 19-1/2 x 2-1/2 | - | - |
| Wheel speed, rpm | 2250 | - | - |
| Air pressure, psi | - | 60 | 55 |
| Work rotation, rpm | 30-50 | 14 | 6 |
| Strip and gage type | Almen #2 | Almen #2 | Almen #2 |
| Arc height, inch | 0.008-0.010 | 0.016 | 0.017 |
| Coverage, percent | 200 | 200 | 200 |

mp