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Abstract

Lightweight and reliable gearboxes are required for helicopters and future electrical vertical take-off and landing aircraft. Mechanical gears in these applications experience more than 10^7 fatigue cycles over their operating life and between maintenance intervals. Fatigue data for gear steels above 10^7 cycles is rare due to the testing time required to reach these cycle counts with traditional methods. In this paper, ultrasonic fatigue testing is used to collect mechanical fatigue data on AMS 6308 steel in the 10^7 to 10^{10} cycle regime.

1.0 Introduction

Lightweight and reliable gearboxes are required for helicopters and future electrical vertical take-off and landing aircraft. Mechanical gears in these applications experience more than 10^7 fatigue cycles over their operating life and between maintenance intervals. High strength materials have been shown to fail due to fatigue past 10^7 stress cycles (Ref. 1). In this fatigue regime, the initiation point for the fatigue crack shifts from the surface to internal defects in the material, and the fatigue stress versus cycles curve has a different slope than the low-cycle fatigue regime (Refs. 1 to 4).

Traditional methods of predicting gear fatigue strength past 10^7 cycles rely on empirical extrapolation of the 10^7 traditional fatigue strength of the material (Refs. 5 and 6). Extrapolation is used because data for gear steel strength past 10^7 cycles is rare due to the time and cost of testing to these high cycle counts using traditional fatigue testing methods. Ultrasonic fatigue testing is a material testing method that allows fatigue stress cycles to be generated in a specimen at 20 kHz, and correspondingly this method is practical for creating material fatigue data in the very high cycle fatigue regime (10^7 to 10^{10} cycles) (Ref. 1). Ultrasonic fatigue can lead to slightly different material fatigue strength predictions relative to predictions obtained with traditional fatigue test methods due to environmental effects, temperature rise, and the low stressed volume in the specimens (Ref. 7).

In this paper, ultrasonic fatigue testing results for “core hardened” AMS 6308 gear steel are presented. AMS 6308 is a gear and bearing steel with high tempering resistance and high hot hardness case targeted to high temperature applications (Ref. 8). The material tested in this paper is “core hardened” such that it is representative of gear tooth core material. Core hardening of the material is accomplished by masking the specimens and processing through the normal AMS 6308 case hardening heat treatment process. Core material strength is not directly applicable to the bending fatigue strength of gear teeth; however, understanding core material strength establishes a baseline for strength improvements achieved through case carburizing and could provide valuable information for the development of heat treatments for very high cycle fatigue strength. Since crack initiation shifts form the surface to internal location in the specimen in the very high cycle fatigue regime, achieving the right combination of case depth and residual stress could extend gear steel lifetimes. The results in this paper will be used to inform future ultrasonic AMS 6308 bending fatigue testing using the method described in Reference 9 that is able to capture the effects of gear tooth heat treatment in a relevant bending fatigue stress environment.

This paper is organized such that Section 2.0 discusses the specimen design, Section 3.0 shows the experimental setup, Section 4.0 presents the testing results, and Section 5.0 provides a conclusion.

2.0 Specimen Design

Past work by the author (Ref. 10), showed that using an axial ultrasonic fatigue specimen design as described in Reference 1 led to significant uncertainty of the stress state of the specimen since the ultrasonic horn used to excite the test specimen has an observable displacement noise level of ~0.05 µm. For the specimens in this paper, a new specimen design was carried out with the goal of reducing the uncertainty of the stress state to less than 1 percent. The dynamic modules of test specimens were measured using the method described in Reference 1. A mean value for the measured material dynamic module based on seven specimens was 201.8 GPa. This measured value was used in all specimen modeling. Appendix A provides the specimen drawing (Figure 4) and specimen test results (Table I) for the dynamic modules of core hardened AMS 6308.

Appendix B provides the drawing for the developed AMS 6308 specimen (Figure 5). Minimum size end sections that are 10 mm long are used to reduce the slope of the stress versus displacement response of the specimen such that a 0.05 µm displacement uncertainty results in a stress uncertainty of ~1 MPa. Finite element analysis was used to achieve the specimen design. Figure 1 shows the FEA model results for specimen mode shape deformation and stress response.

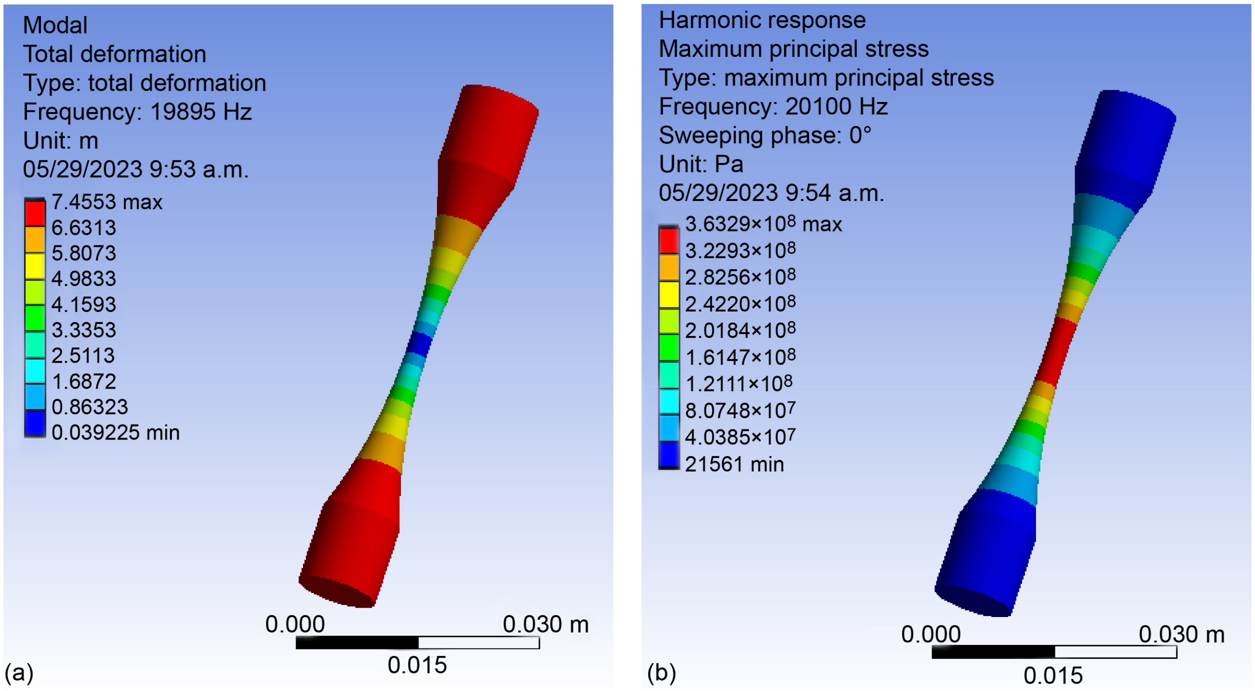


Figure 1.—Developed specimen FEA models. To the left shows modal analysis result. To the right shows harmonic response of the specimen at 20,100 Hz.

The specimen manufacturing was carried out in a four step process:

1. Premachining per drawing (Figure 6) in Appendix C
2. Heat treatment per process defined in Appendix D
3. Low stress grind the gage section to desired dimensions.
4. Final machine the part to length. Appendix B provides final part geometry (Figure 5)

One error occurred during fabrication of the test specimens. The machining process used to final cut the parts to length led to scratches in the gauge section that resulted in premature fatigue failure of some preliminary specimens. After this observation of test results from preliminary specimens, hand polishing was used to improve the surface finish. However, the hand polishing was not a well-controlled process, and should be noted as a possible source of error in the reported stress values the results in Section 4.0.

3.0 Experimental Setup

The experimental setup for the testing is shown schematically in Figure 2. A piezo electric actuator-based ultrasonic fatigue tester is used (Ref. 1). The tester consists of a data acquisition system, an ultrasonic wave generator, a piezo electric actuator, and a resonance horn. The tester runs using displacement control. A specified displacement is set by the user and the ultrasonic wave generator controls the amplitude and frequency of the 20 kHz electrical wave it supplies to the piezo actuator to achieve the required displacement with minimal energy consumption. The piezo actuator produces a very small displacement sinusoidal wave at the frequency provided by the wave generator. The resonance horn attached to the end of the actuator is used to amplify the piezo actuator’s displacement to the target testing displacement. The resonance horn is design to have a longitudinal mode at 20 kHz. If a specimen with a mode close to 20 kHz is attached to the end of the horn, the mode will be excited and stress/displacement cycles can be generated in that part corresponding to that mode shape of the specimen.

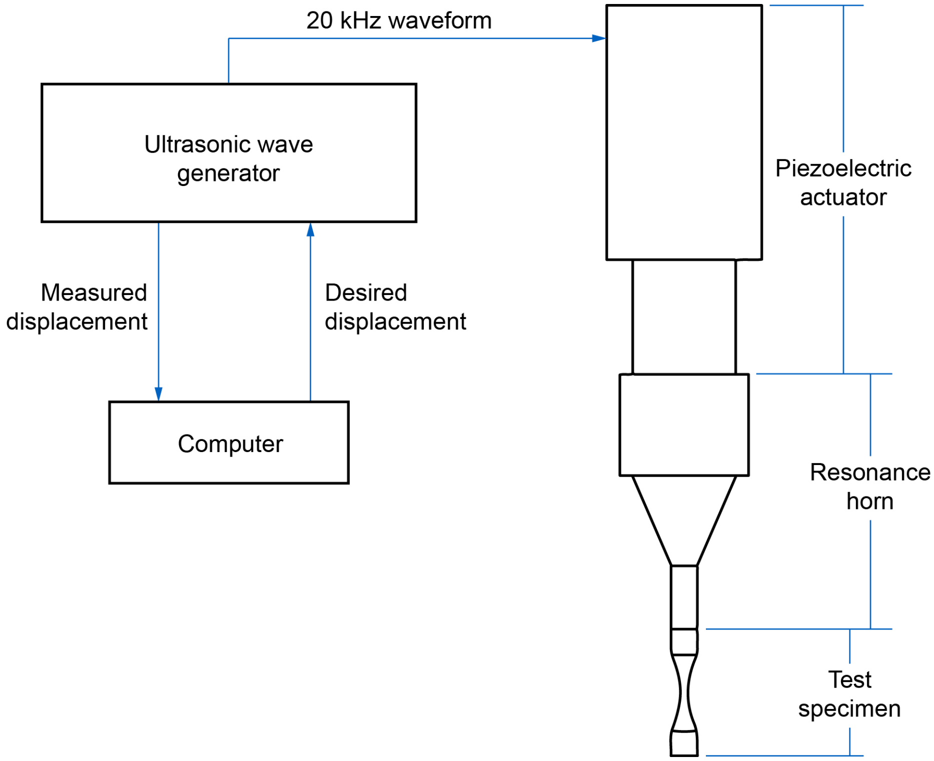


Figure 2.—Schematic depiction of the ultrasonic fatigue rig.

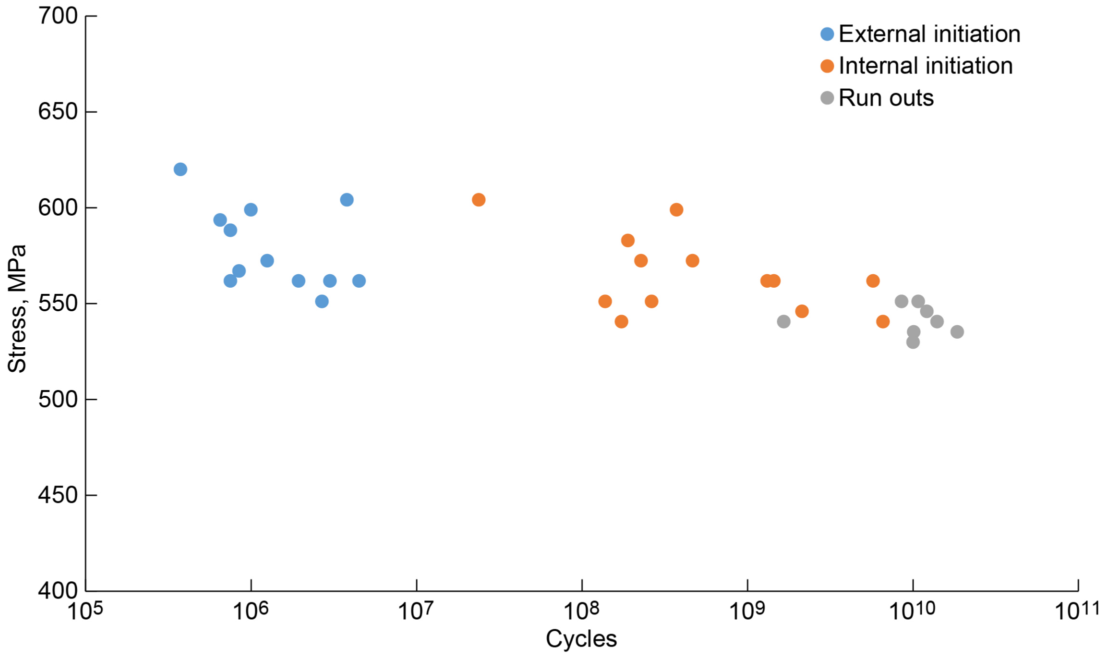


Figure 3.—Peak specimen stress versus cycles to failure for core hardened AMS 6308.

4.0 Testing Results

Thirty-three specimens were produced and tested. The results in terms of stress and cycles are shown in Figure 3. Stress is reported as calculated form FEA using the measured dynamic modules of the steel of 201.8 GPa. A number of points are shown to fail due to external defects at less than 10^7 cycles. These test points are believed to have been affected by the manufacturing process damaging their surfaces as discussed in Section 2.0. Regardless, in ultrasonic fatigue, fractures that occur at less than 10^7 cycles are typically significantly affected by heat generation and correspondingly should not be considered representative of the material strength.

Twelve total specimens fractured in the range of 10^7 to 10^{10} cycles with initiation sites internal to the specimens. Fatigue strengths fell in the range of 550 MPa around the expected strength for core hardened gear steels. Seven total specimens were runout to 10^{10} cycles at stresses slightly less than 550 MPa. The lowest fracture strength for a specimen prior to 10^{10} cycles was 540 MPa.

5.0 Conclusions

In this paper ultrasonic fatigue testing results for core hardened AMS 6308 were presented. Fatigue data was collected for the material in the range of 10^7 to 10^{10} fatigue cycles. Failure strengths were found to be in the range of 540 to 600 MPa for the stress cycle regime past 10^7 cycles. Seven total specimens were runout to 10^{10} cycles at stress levels around or below 540 MPa. These results are not directly applicable to the bending fatigue strength of AMS 6308 in case carburized gear teeth. However, these results provide a baseline strength dataset for future bending fatigue tests of carburized ultrasonic bending fatigue specimens and could provide some valuable information for understanding gear failure or for refining heat treatments to accomplish long-life gears for aviation applications.

Appendix A.—Dynamic Modules Testing Results

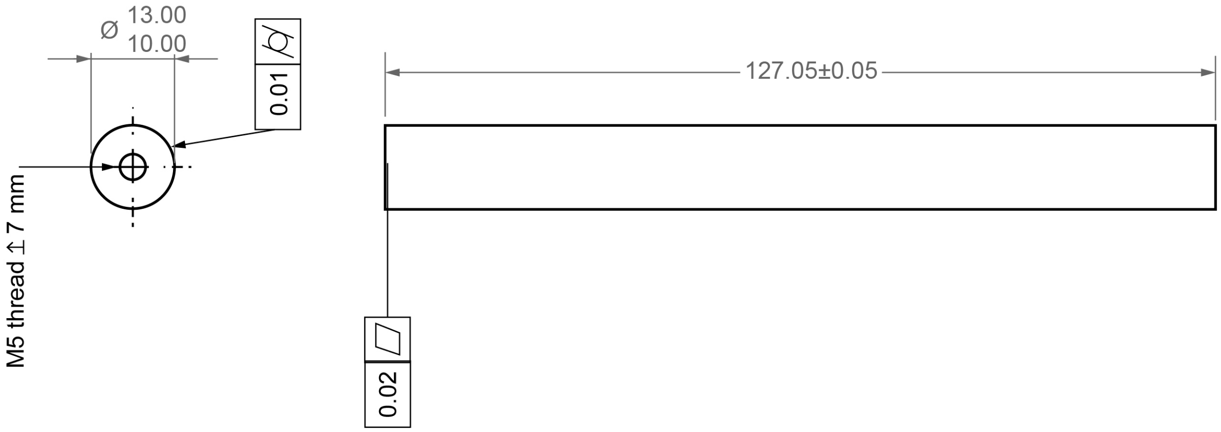


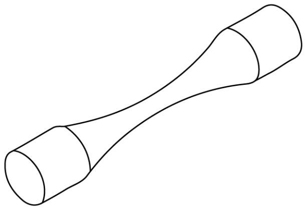
Figure 4.—Dynamic modules testing specimen.

TABLE I.—DYNAMIC MODULES TESTING RESULTS

Specimen no.	Length, m	Density, kg/m^3	Frequency, Hz	Ed, Pa
1	1.27×10^{-1}	7.85×10^{3}	2.00×10^{4}	2.05×10^{11}
2	1.27×10^{-1}	7.88×10^{3}	1.98×10^{4}	2.01×10^{11}
3	1.28×10^{-1}	7.87×10^{3}	1.98×10^{4}	2.01×10^{11}
4	1.28×10^{-1}	7.87×10^{3}	1.98×10^{4}	2.02×10^{11}
5	1.27×10^{-1}	7.88×10^{3}	1.99×10^{4}	2.02×10^{11}
6	1.27×10^{-1}	7.88×10^{3}	1.98×10^{4}	2.01×10^{11}
7	1.27×10^{-1}	7.87×10^{3}	1.98×10^{4}	2.01×10^{11}

Appendix B.—Specimen Geometry

Notes:
- Dimensions are in mm
- Material is Pyrowear 53 through hardened to HRC42
- Min. 3.2 µm Ra all over except where specified
- Low stress grind gage section
- Inspection report required for gage diameter and gage runout



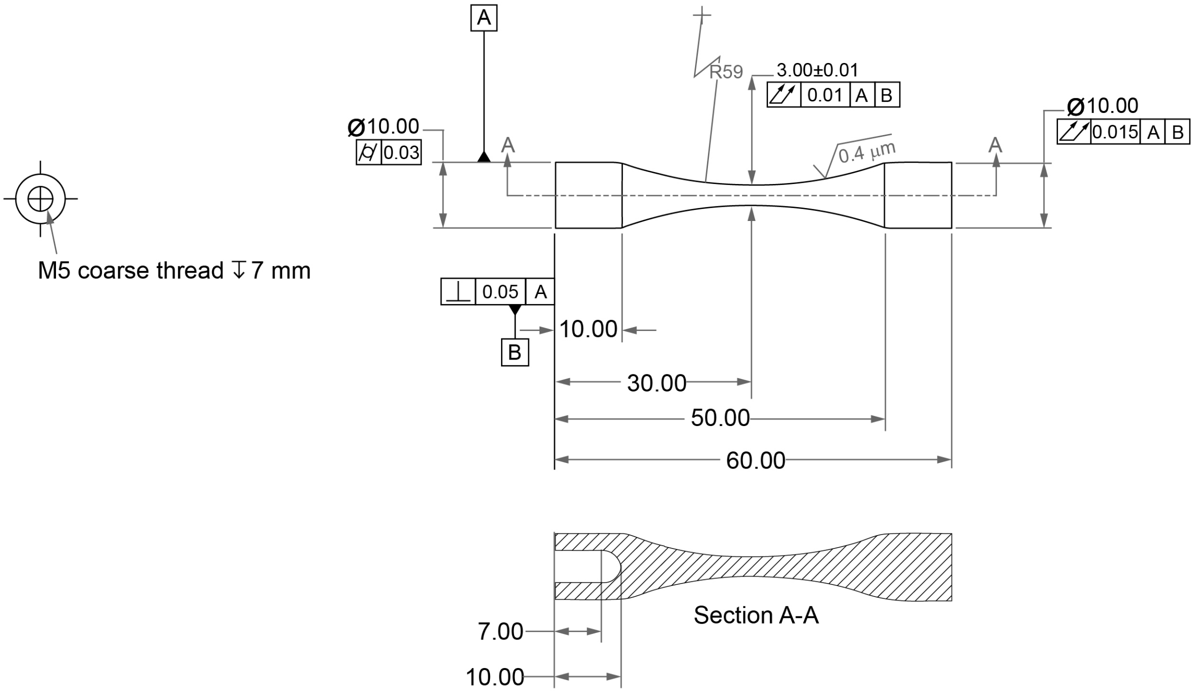


Figure 5.—Final specimen geometry drawing.

Appendix C.—Premachined Geometry

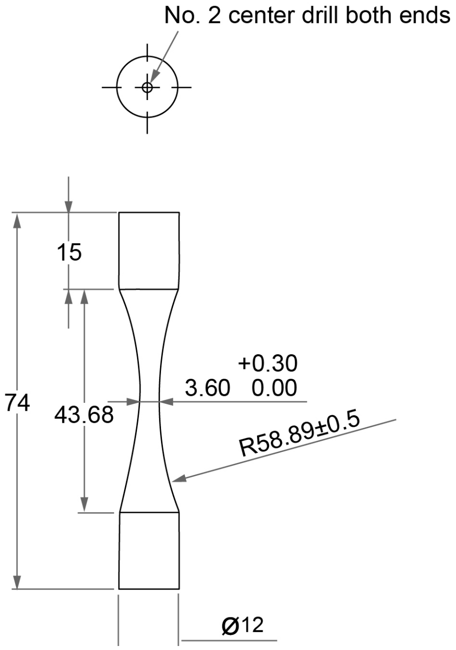


Figure 6.—Preheat treatment and grinding specimen geometry.

Appendix D.—Heat Treatment

1. Copper plate specimens
2. Heat to 1700 °F and hold 7 h in inert gas environment.
3. Slod cool to room temperature.
4. Reheat to 1675 °F and hold for 25 min in vacuum environment.
5. 10 Bar N2 Gas Quench
6. Refrigerate to –100 °F for 30 min
7. Temperature at 400 °F for 2 + 2 h

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