JOURNAL OF AIRCRAFT
Vol. 46, No. 5, September–October 2009

Fatigue Performance of Nitrided Aircraft Crankshafts

John M. Barsom
Barsom Consulting, Ltd., Pittsburgh, Pennsylvania 15217

DOI: 10.2514/1.39672

A study of the fatigue strength of full-size nitrided crankshafts made with 4340 vacuum arc remelting steel is presented. This investigation was undertaken in response to several in-flight failures of crankshafts in aircraft engines. The absence of fatigue endurance limit data for full-size, nitrided crankshafts made from 4340 vacuum arc remelting steel was specifically noted by the Federal Aviation Administration. Both nitriding and size effects are known to increase the fatigue strength typically reported for 4340 vacuum arc remelting steel using unnitrided, cylindrical rotating-beam test samples. Full-size nitrided crankshafts were tested in complete load reversal and were found to have a fatigue endurance limit of approximately 160 ksi. This value was found to be in excellent agreement with theoretical predictions using fracture-mechanics analyses and with prior fatigue testing of full-size nitrided crankshafts using air-melted 4340 steel.

Introduction

FOR decades, the aerospace industry has used 4340 vacuum arc remelting (VAR) steel in high stress applications with excellent results. A substantial body of data on the fatigue strength of 4340 VAR steel has been developed using cylindrical rotating-beam test specimens. These data, however, are of limited utility when predicting the fatigue strength of nitrided aircraft parts because the compressive residual stresses and increased strength of the surface imparted by the nitriding process significantly increase the fatigue strength. Moreover, because the amount of residual compressive stress is dependent upon the size and configuration of the actual part, simply nitriding unrestrained cylindrical test specimens does not adequately predict the fatigue strength of the part [1]. Thus, the actual part or a representative section having the same geometry and size as the actual part must be investigated to determine fatigue strength in service.

The present investigation was undertaken in response to several in-flight failures of crankshafts in aircraft engines. The absence of fatigue endurance limit data for full-size, nitrided crankshafts made from 4340 VAR steel was specifically noted by the Federal Aviation Administration [2]. The research presented here investigates, both in theory and experiment, the fatigue strength of a full-size, nitrided crankshaft made with 4340 VAR steel for use in reciprocating piston aircraft engines.

The crankshafts investigated in this investigation were forged from desulfurized and deoxidized 4340 VAR steel. "AISI/SAE 4340 steel is considered the standard to which other ultra-high-strength steels are compared. It combines deep hardenability with high ductility, toughness, and strength. It has high fatigue resistance and is often used where severe service conditions exist and where high strength in heavy sections is required" [3]. 4340 steel is forged usually between 1065 and 1287°C (1949 and 2350°F) [3–5].

The VAR "process can produce very sound ingots of dense crystal structure, low hydrogen and oxygen contents, and with minimal chemical segregation" [6]. "Vacuum melting, which reduces the number and size of nonmetallic inclusions, increases the fatigue limit of 4340 steel" [4]. The 4340 VAR steel for the crankshafts was desulfurized and deoxidized. The sulfur content of the steel was about 0.001% or less. The hardness of the 4340 VAR crankshaft steel ranged from 32.7 to 35.8 HRC (Rockwell hardness C scale) which corresponds to tensile strengths between about 148 and 160 ksi.

Received 9 July 2008; revision received 20 January 2009; accepted for publication 3 April 2009.

The crankshafts investigated were nitrided to develop a compressive residual stress layer on the surface. The hardness of the nitrided layer was about 69 HR30N (45–51 HRC) which corresponds to a tensile strength of about 260 ksi.

A photograph of the crankshafts tested is shown in Fig. 1. The crankshaft consists of six crankpin journals, four main bearing journals and an integral flange to which the propeller is attached. Each of the crank pins has a bearing surface that is subjected to piston combustion loads through a connecting rod. Two dynamic counterweights that are located on the rear long cheek of the crankshaft control torsional vibration and therefore control torsion stresses. A gear at the rear of the shaft drives the camshaft and most accessories. The combustion forces applied by the pistons cause the crankshaft to twist and bend. Under these applied loads and crankshaft geometry, the stresses are higher at the fillet radii than in the body of the cheeks or journals. Multimodal finite element (FE) analyses and experimental measurements [2] demonstrated that the highest stresses in the crankshaft under operating conditions occur at the fillets on either side of cheek 8 at crankpins 5 and 6.

Nitriding

> Compression residual stresses at the surface of a part can improve its fatigue life. . .. Beneficial compressive residual stresses may be produced by surface alloying, surface hardening, mechanical (cold) working of the surface, or by a combination of these processes. In addition to introducing compressive residual stresses, each of these processes strengthens the surface layer of the material. Because most real components also receive significant bending and/or torsion loads, where the stresses are highest at the surface, compressive surface stresses can provide significant benefit to fatigue [7].

Nitriding is a process of case hardening in which steel components are heated in a nitrogen environment [8]. Gas nitriding is the most widely used production process of nitriding. It is carried out in an atmosphere of ammonia at temperatures between about 500°C (932°F) and 560°C (1076°F). The components are exposed to this environment for different times depending on steel composition and the desired depth of the nitrided case. Ammonia is adsorbed and dissociates into nitrogen and hydrogen atoms at the surface of the hot steel. The nitrogen atoms dissolve in the steel and migrate away from the surface. When nitrogen concentration exceeds the maximum soluability of the matrix, nitrogen combines with alloying elements to form nitrides. The precipitated nitrides increase the case hardness and subject the nitrided case to compressive residual stresses. These changes produce a case that has high resistance to wear and increases the fatigue resistance of the nitrided component [8,9].

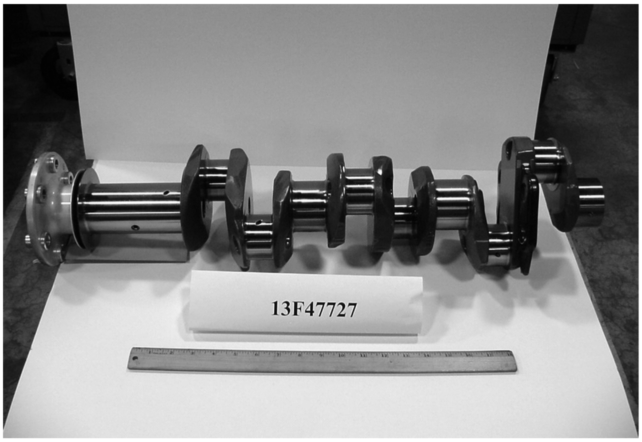

Fig. 1 Six cylinder 707 crankshaft.

The high hardness of the nitrided case inhibits the initiation of fatigue cracks [10]. The compressive residual stresses prevent fatigue crack propagation [10]. The combined effects of high hardness and compressive stresses prevent initiation of fatigue cracks from the surface of crankshafts. In the presence of discontinuities, nitriding shifts the fatigue-crack-initiation site from the surface to the core of the specimen [11–14].

Under tension–tension cyclic loads, the entire core volume is subjected to the same stress fluctuation. Thus, fatigue cracks initiate and propagate from the most severe discontinuity within the entire uniformly stressed core material. The stress necessary to initiate and propagate the fatigue crack decreases as the discontinuity becomes more planar (i.e., cracklike) and its projection perpendicular to the direction of the tension stress increases. In bending and torsion, the superposition of the residual stresses induced by nitriding and the applied cyclic stresses produce maximum tension cyclic stress at the transition zone between the case and the core. Also, the magnitude of the cyclic tension stresses decrease away from the surface. Consequently, the fatigue damage decreases because the probability of having a large discontinuity at the highly stressed location decreases with decreasing volume of material subjected to tensile stress [14]. Thus, when fatigue failure occurs in nitrided specimens subjected to bending or tension, "subsurface fatigue crack initiation called 'fish eye' is dominated in nitrided steel with the contribution of inclusions" although in the unnitrided steel fatigue cracks initiated at inclusions on the surface of the specimens [13]. Tests by Siqueira et al. demonstrated that "All (nitrided) specimens presented the same characteristics, that is, the fatigue process initiated from inclusions. It is well known that, from nitriding process, the crack initiation always occurs from an internal inclusion" which was the case for all of their tested specimens [12].

Fatigue Crack Initiation from the Surface of Fillets

Traditionally, the fatigue endurance limit has been determined by testing smooth, cylindrical specimens in constant amplitude rotating-beam bending where the maximum tension and compression in each cycle have equal absolute values (i.e., $R = -1$). Test results are plotted as *S-N* curves where S is the maximum tension stress in a cycle and N is the number of cycles to failure. The total tension plus compression stress range in a cycle is equal to $2S$. Fatigue endurance limit defines the stress range above which fatigue cracks initiate and propagate to failure and below which fatigue cracks do not initiate resulting in infinite fatigue life. It is generally accepted that the fatigue endurance limit for steels under full reversal ($R = -1$) loading is equal to about one-half the ultimate tensile strength of the steel. Also, in the absence of subsurface discontinuities, fatigue cracks initiate on the surface of rotating-beam specimens.

Fracture-Mechanics Considerations

Fracture-mechanics theory relates the intensity of the stress field at the tip of a crack or a cracklike discontinuity, such as a notch, to the applied stress and to the size of the crack. This relationship is represented by the equation [10]

$$K = \sigma(\pi a) f(g) 1/2 \tag{1}$$

where K is the stress intensity factor, σ is the applied stress, a is the crack size, and $f(g)$ is a function whose value depends on the geometry of the crack and of the component. Fatigue damage occurs at the tip of a crack or a notch and is caused by the change in the applied stress, $\Delta\sigma$. Thus, under cyclic loads, σ becomes $\Delta\sigma$ and K becomes ΔK and Eq. (1) becomes [10]

$$\Delta K = \Delta\sigma(\pi a) f(g) 1/2 \tag{2}$$

Fatigue Crack Initiation: General Discussion

Notches in structural components cause stress intensification in the vicinity of the notch tip. The material element at the tip of a notch in a cyclically stressed structural component is subjected to the maximum stress fluctuation, $\Delta\sigma_{\max}$. Consequently, this material element is most susceptible to fatigue damage and is, usually, the site of fatigue crack initiation.

The maximum stress at the notch tip may be approximated from the relationship:

$$\sigma_{\max} = k_t \sigma = 2K_I/(\pi\rho) 1/2 \tag{3}$$

and the maximum stress range by the relationship:

$$\Delta\sigma_{\max} = k_t(\Delta\sigma) = 2\Delta K_I/(\pi\rho) 1/2 \tag{4}$$

where $\Delta K_I = \Delta\sigma(a_n) 1/2$, a_n is the notch length, k_t is the stress-concentration factor for the notch, and ρ is the notch tip radius.

The fatigue-crack-initiation life of notched specimens decreases as the notch tip radius decreases. Similarly, for a fixed notch tip radius, the fatigue-crack-initiation life of a notched specimen decreases as the notch length increases. The combined effects of notch tip radius and notch length on fatigue-crack-initiation life can be predicted by using the correlating parameter $\Delta K/(\rho) 1/2$ [10].

The data in Fig. 2 suggest the presence of a fatigue-crack-initiation threshold, $\Delta K/(\rho)]_{\text{th}} 1/2$, below which fatigue cracks would not initiate at the tip of a stress riser such as notches or fillets. The presence of a fatigue-crack-initiation threshold was established for steels having yield strengths between 36 and 110 ksi, Fig. 3 [10]. The data in Fig. 3 demonstrate that the stress ratio (ratio of minimum stress and maximum stress) had negligible effect, if any, on the fatigue-crack-initiation threshold for notches or similar stress risers when the parameter $\Delta K/(\rho)]_{\text{th}} 1/2$ is based on the total stress (tension and compression) range. Thus, the data indicate that fatigue-crack-initiation damage caused by a compressive stress range is equal to the damage caused by a tension stress range of the same absolute magnitude. These observations are directly applicable to the fillet radii between the journals and the cheeks of the crankshafts. The high strength and the compressive stresses on the surface of a nitrided fillet inhibit the initiation and propagation of fatigue cracks from the surface of the fillet.

Although the fatigue-crack-initiation threshold, that is, endurance limit, for steels is determined by the total (tension and compression) stress range, the finite fatigue lives above the endurance limit for specimens subjected to these cyclic stresses are significantly different because propagation of an initiated crack is governed primarily by the tension component of the stress cycle. Cracks that initiate under tension–tension or compression–tension stress fluctuation would propagate to critical sizes causing fractures. However, cracks that initiate under compression–compression stress fluctuation would not propagate resulting in infinite fatigue life for the components.

Computing Fatigue-Crack-Initiation Threshold for Aircraft Crankshafts

Method I: Measurements made on crankshafts showed that the minimum surface hardness of the nitrided case was 69 HR30N

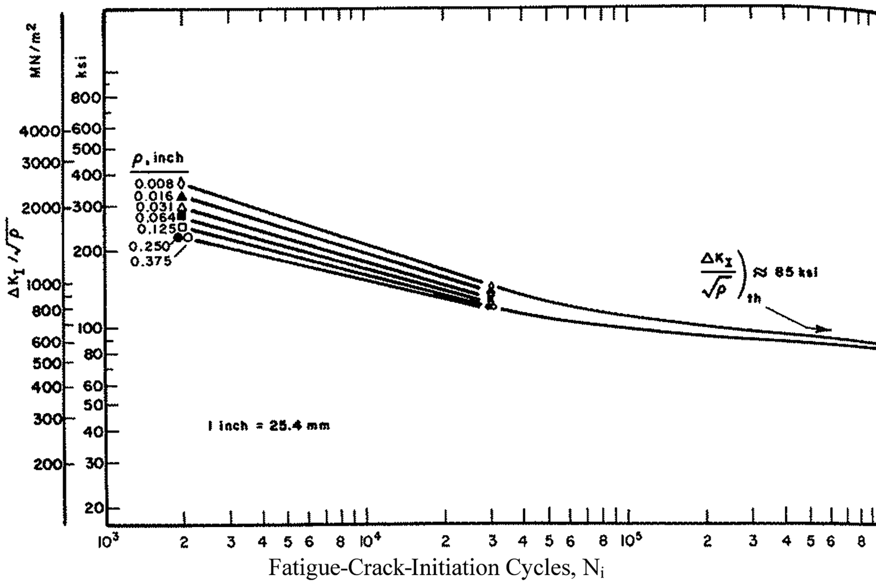

Fig. 2 Correlation of fatigue-crack-initiation life with the parameter $\Delta K_I/\sqrt{\rho}$ for an HY-130 steel.

(45–51 HRC). This value indicates that the minimum tensile strength of the nitrided case of the fractured crankshaft was about 1789 MPa (260 ksi). The fatigue endurance limit under full reversal ($R = -1$) for steel of this strength would be one-half the 260 ksi tensile strength, that is, 130 ksi. Finite element analyses indicate that the maximum applied stresses at the surface of the most stressed fillet in the crankshaft are about ±613 MPa (±89.2 ksi) [6]. The maximum applied stress at this location is less than the endurance limit of the nitrided crankshaft. Therefore, based on material properties alone, fatigue cracks would not initiate from the surface of the nitrided case under operating conditions.

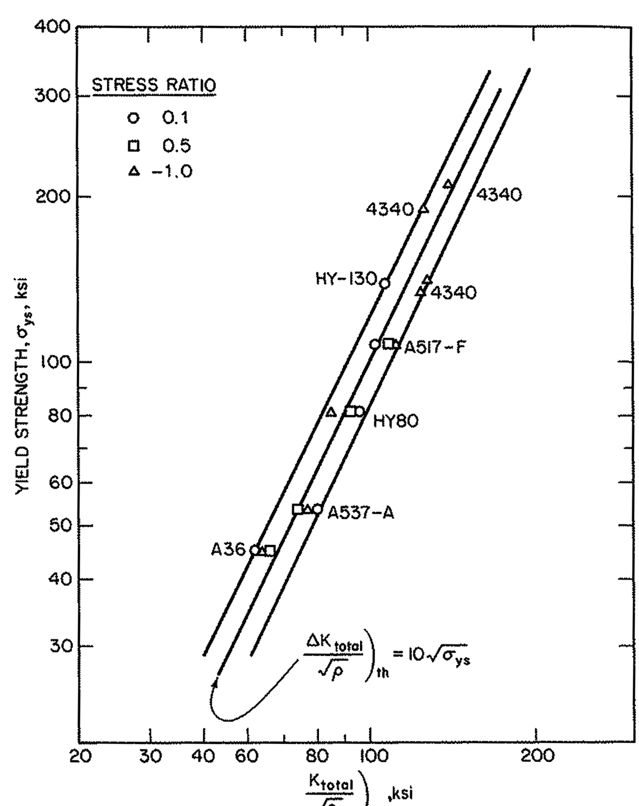

Fig. 3 Dependence of fatigue-crack-initiation threshold on yield strength.

Experimental measurements indicate that the maximum residual compressive stress on the surface of the nitrided fillet is about −120 ksi, Fig. 4 [15]. When the most highly stressed fillet is subjected to the maximum applied tension and compression stresses of about 90 ksi, the surface of the fillet fluctuates between a maximum stress of about −30 ksi and a minimum stress of −210 ksi. Cracks do not propagate under compression–compression cyclic stresses. Therefore, small cracks on the surface of the nitrided fillet would not propagate. Consequently, in the absence of subsurface microcracks or other subsurface defects, the nitrided crankshafts would have infinite fatigue life under the most severe operating conditions of constant full engine power.

The fatigue endurance limit for the 4340 VAR nitrided crankshafts can be calculated from the sum of the endurance limit based on material properties alone (i.e., 130 ksi), the tensile stresses required to overcome the surface compressive stress (i.e., 30 ksi), and the additional tensile stress required to propagate a crack. This latter stress value is computed from the threshold stress intensity factor for fatigue crack propagation [10].

The threshold stress-intensity-factor range, ΔK_{th}, defines the highest stress fluctuation above which a crack would propagate. The threshold stress-intensity-factor range for long cracks subjected to fully reversed stresses is about 5.5 ksi (in.)1/2, Fig. 5 [10]. The threshold stress-intensity-factor range for a short crack subjected to fully reversed stresses is about 4.2 ksi (in.)1/2 [16]. The thickness of the nitrided layer in the crankshafts typically ranges from 0.018 and 0.024 in. Assuming that the nitrided surface layer has a defect of a size equal to the depth of the nitrided layer, the stress to cause the defect to propagate is computed to be between about 13 and 16 ksi with an average of 14 ksi. Summing up the three components of stresses (i.e., 130 + 30 + 14 ksi) results in a computed fatigue endurance limit of 174 ksi.

Method II: The fatigue endurance limit of the crankshaft can be determined by using another fracture-mechanics based relationship. The data in Fig. 3 demonstrate that the endurance limit for steels may be predicted from the relationship [10]:

$$\Delta K_{\text{total}}/\sqrt{\rho} = 10\sqrt{\sigma_{\text{ys}}} \tag{5}$$

where σ_{ys} is the room temperature yield strength of the steel.

Combining Eqs. (4) and (5) shows that the maximum stress at the fillet radius corresponding to the endurance limit is given by

$$\Delta\sigma_{\max} = (2/\sqrt{\pi}) \times (10\sqrt{\sigma_{\text{ys}}}) \tag{6}$$

The nitrided crankshaft surface is a very high strength steel. The outer surface of the nitrided layer exhibits an ultimate tensile strength of

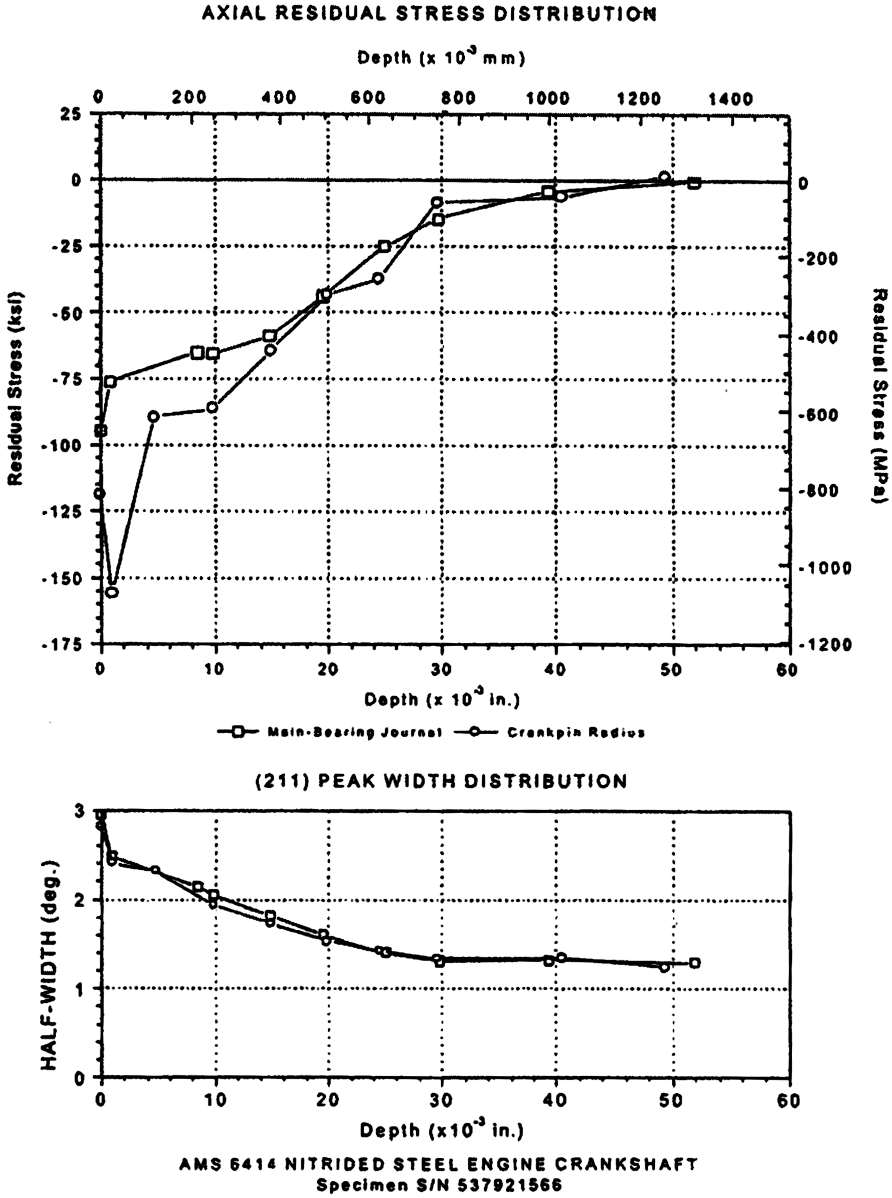

Fig. 4 Axial residual stress distribution in the nitrided case.

about 260 ksi. The yield strength of the nitrided layer is estimated to be about 250 ksi. Substituting this yield strength value in Eq. (6) computes a fatigue endurance limit of 171 ksi. This value is in excellent agreement with the 174 ksi value that was predicted earlier using a different fracture-mechanics based analysis.

Experimental Determination of Fatigue Endurance Limit for Crankshafts

The present investigation was conducted to determine experimentally the endurance limit of crankshafts provided by Lycoming Engines. The tests were conducted on press forged six cylinder crankshafts, Fig. 1. Steel making and forging temperatures for the aircraft quality steel were carefully controlled to ensure defect free crankshafts. Crankshaft dimensions and depth of the nitrided layer were in conformance with the Lycoming specifications.

Test Procedure

The fatigue endurance limit for the crankshaft could be determined by subjecting the crankshaft or a segment of the crankshaft to either bending or tensile stresses. The primary requirement is to be able to compute accurately the stresses at the fillet where the fatigue crack will initiate. Also, because the fatigue endurance limit is governed by material properties and the maximum stress fluctuation, the value of the endurance limit determined for a fillet at one location is equally valid for other fillets.

Multimodal finite element analyses demonstrated that the highest stresses in the crankshaft under operating conditions occur at the fillets on either side of cheek 8 at crankpins 5 and 6. Therefore, the test specimens in the present investigation were sections geometrically symmetrical about cheek 8. The sections contained cheeks 7, 8, and 9, crankpins 5 and 6, and bearing journals 3 and 4. A photograph of a test specimen is presented in Fig. 6. Bearing journals 3 and 4 were threaded and screwed into the grips of a servohydraulic machine. The specimens were tested in full reversal. The grip ends were kept 3/4 in. away from the adjacent surfaces of cheeks 7 and 9 to prevent interference between the grips and the test specimen. The selected specimen and loading resulted in accurate prediction and control of the fully reversed cyclic stresses at the fillets.

Stress Analysis

FE analysis was conducted by LMS North America on the axially loaded test specimens to determine the location of maximum stress and the relationship between the applied loads and the maximum stress magnitude. A layer of very thin shell elements, shown in Fig. 7, was created to compute stresses. The FE analysis for axial loading

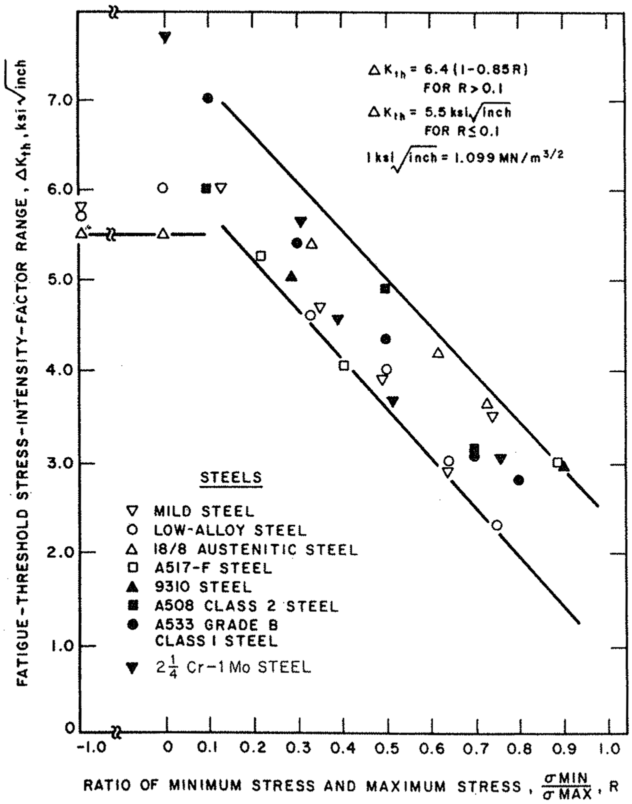

Fig. 5 Dependence of fatigue-threshold stress-intensity-factor fluctuation on stress ratio.

with freed radial and rotational degrees of freedom demonstrated that maximum stresses for the axially loaded specimen occur at the fillet between crankpin 6 and cheek 9. At an applied 15,835-lb axial force, the maximum stress at the fillet was computed to be 172 ksi.

Fatigue endurance limits are determined by subjecting each specimen to precisely determined and controlled minimum and maximum stresses. At high stress ranges, fatigue cracks initiate and propagate to failure resulting in a finite fatigue crack initiation and propagation life. As the stress range decreases, the number of cycles to initiate a crack increases until a stress range value is reached where cracks do not initiate regardless of the number of applied cycles. Fatigue endurance limit is defined by the largest stress range that would not initiate a fatigue crack and where the component exhibits infinite life.

Test Results

Infinite Fatigue Life: Fatigue Endurance Limit

The fatigue performance of nitrided crankshafts was determined by Boegehold [1]. The tests were conducted on 4340 steel that was

Fig. 6 Picture of test specimen.

No. of Nodes	180,360
No. of Elements	138,032

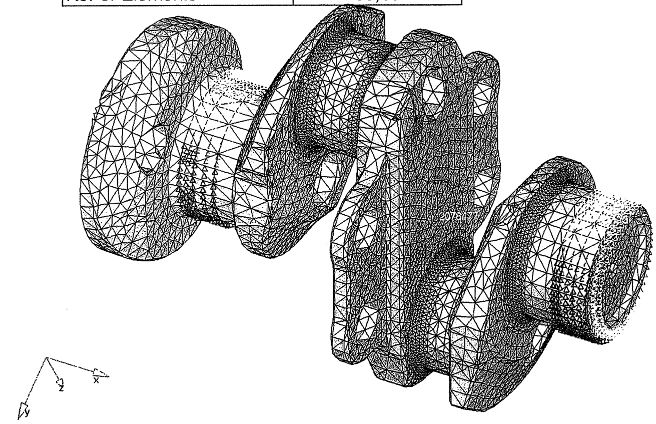

Fig. 7 Finite element model of test specimen.

not processed to clean steel practice, thus, contained many inclusions. The fatigue performance of the tested crankshafts was influenced by the size and density of the inclusions that initiated the fatigue failures. The data demonstrate that nitriding increased the fatigue endurance limit of air-melted 4340 crankshafts by about 50%. The fatigue endurance limit for the nitrided crankshafts made of air-melted 4340 steel ranged from "120,000 to 130,000 psi," Fig. 8 [1].

The 4340 VAR steel of the crankshafts that were tested in the present investigation was desulfurized, deoxidized, and vacuum arc melted. Thus, unlike the steel tested by Boegehold, this steel would contain a negligible number of inclusions. Consequently, the fatigue endurance limit for the crankshafts tested in the present investigation would be higher than 120 to 130 ksi.

The fatigue performance of the crankshafts tested in the present investigation is presented in Fig. 9. The *S-N* data demonstrate that the fatigue endurance limit for the Lycoming crank shafts is between 161 and 165 ksi. This value is in excellent agreement with the theoretically determined fracture-mechanics based values of 171 and 174 ksi.

Finite Fatigue Life

The finite fatigue life data in Fig. 9 represent the number of cycles required to initiate a fatigue crack plus the number of cycles to propagate the crack from a subcritical size to a critical dimension which fractures the test specimen. As the stress range increases the number of cycles to initiate and propagate a crack to critical dimensions decreases. The fatigue crack in the axially loaded crankshaft specimen tested in this investigation initiated at a location on the fillet defined by the intersection of the fillet and the line at midwidth of the cheek. Figure 10 shows a typical fatigue crack initiation from the surface of a fillet in the tested crankshaft. Once initiated, crack propagation in the absence of the fillet stresses is along a plane that is perpendicular to the maximum applied stress component. This crack propagation plane is inclined about 22.5 deg into the cheek away from the plane of the fillet. However, the high stresses at the fillet

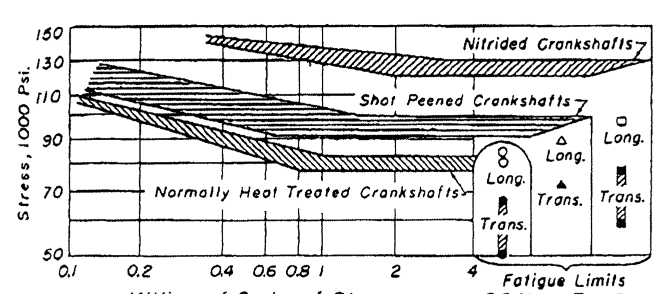

Fig. 8 Fatigue endurance limit of air-melted and nitrided 4340 alloy steel crankshafts and rotating-beam test specimens (Boegehold [1]).

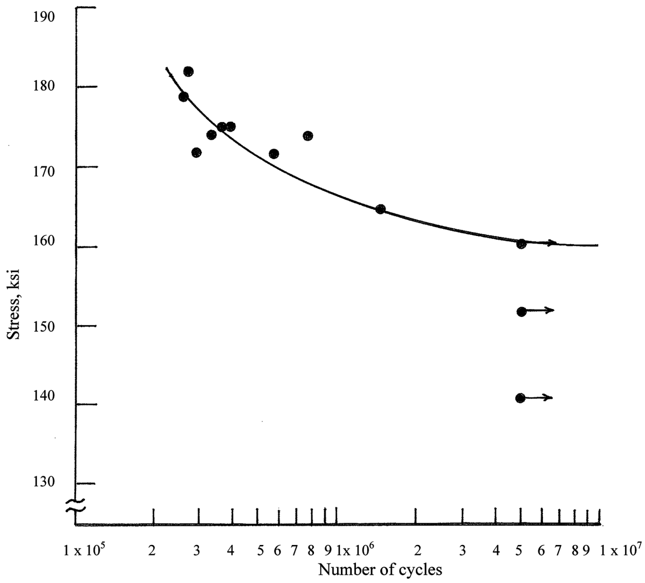

Fig. 9 Fatigue endurance limit of nitrided 4340 VAR steel press forged crankshafts made to clean steel practice.

radius initiate secondary cracks. The competition between these two crack driving forces results in a crack propagation path as shown in the examples presented in Fig. 10. The competition between the two driving forces resulted in the propagation of multiple parallel radial cracks to the crankpin. An example of such cracks is presented in Fig. 11. Differences in the crack propagation path resulted in different crack propagation lives among the tested specimens. These differences manifested themselves in variability of total fatigue life among the tested specimens, Fig. 9.

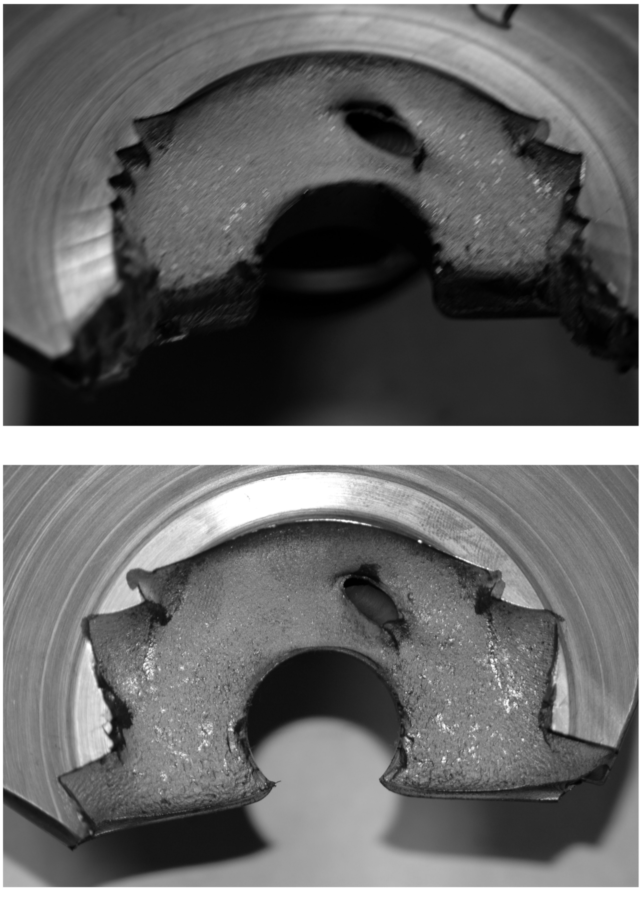

Fig. 10 Fracture surfaces.

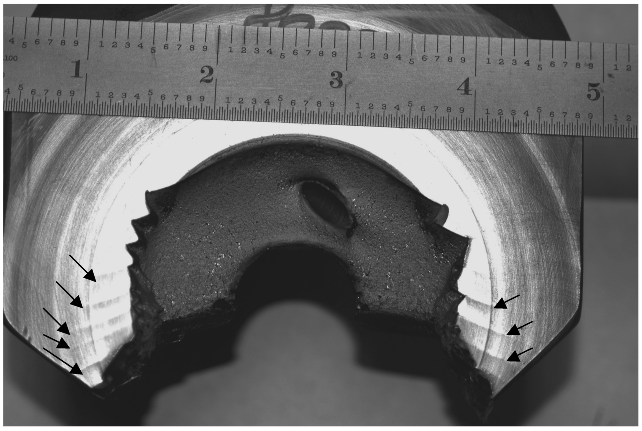

Fig. 11 Multiple fatigue cracks.

Fatigue Behavior Under Service Loads and Under Axial Loads

A crankshaft in service is subjected to transverse loads applied at the crankpins. These loads produce a fully reversed stress at the fillets. The deformations of the crankpins and of the cheeks are governed by the constant displacement of the pistons. Thus, if a crack were to initiate at a crankshaft fillet, it would propagate into the crankpin or the cheek under constant deformation. Consequently, as the crack propagates under service loads the crack driving force defined by the stress-intensity-factor range, ΔK, at the crack tip decreases, the fatigue crack propagation rate decreases, and the fatigue crack propagation life increases [10]. On the other hand, under the constant load conditions used in the present investigation, as the crack size increases the crack driving force increases, fatigue crack growth rate increases, and fatigue crack propagation life decreases. Thus, in service crankshafts would exhibit longer fatigue crack propagation life.

Conclusions

The results of the present investigation to determine the fatigue endurance limit of a nitrided crankshaft made with 4340 VAR steel may be summarized as follows:

1) Rotating-beam test specimens do not accurately predict the fatigue strength of a full-size nitrided crankshaft.

2) The fatigue endurance limit of nitrided 4340 VAR crankshafts was determined analytically to be 171 and 174 ksi.

3) The fatigue endurance limit of nitrided 4340 VAR crankshafts was determined experimentally to be between 161 and 165 ksi.

4) The fatigue crack propagation life of crankshafts under service loads is longer than under axial loads used in the present investigation.

Acknowledgment

The author acknowledges Lycoming Engines for funding this research.

References

[1] Boegehold, A. L., "Test Bar Results Compared with Tests on Components," *Metal Progress*, 1950.

[2] Rumizen, M., Brane, K., Hjelm, J., Naylor, R., Pendleton, P., Swartz, D., Viselli, R., and Queitzsch, C., "Lycoming Special Certification Review Team (SCRT)," Final Report, Federal Aviation Administration, 30 Sept. 2004.

[3] *Metals Handbook: Desk Edition*, edited by H. E. Boyer and T. L. Gall, ASM International, Metals Park, OH, 1985.

[4] *Properties and Selection: Iron, Steels, and High-Performance Alloys*, Vol. 1, 10th ed., ASM International, Metals Park, OH, 1990.

[5] *Forging Handbook*, edited by T. G. Byrer, Forging Industry Association, Cleveland, OH, 1985.

[6] *The Making, Shaping and Treating of Steel*, edited by W. T. Lankford, Jr., N. L. Samways, R. F. Carven, and H. E. McGannon, 10th ed., United

States Steel, Association of Iron and Steel Engineers, Pittsburgh, PA, 1985.
[7] *Properties and Selection: Iron, Steels, and High-Performance Alloys*, Vol. 1, 10th ed., ASM International, Metals Park, OH, 1990.
[8] *ASM Engineering Bookshelf: Source Book on Nitriding*, ASM International, Metals Park, OH, 1977.
[9] *Metals Handbook: Desk Edition*, edited by H. E. Boyer, and T. L. Gall, ASM International, Metals Park, OH, 1985.
[10] Barsom, J. M., and Rolfe, S. T., *Fracture and Fatigue in Structures: Applications of Fracture Mechanics*, 3rd ed., ASTM MNL41, ASTM International, West Conshohocken, PA, 1999.
[11] Almen, J. O., "Peened Surfaces Improve Endurance of Machine Parts," *Metal Progress*, Feb. 1943.
[12] Siqueira, C. P., Pereira, C. P. M., Nascimento, M. P., Voorwall, H. J. C., and Souza, R. C., "Effects of Nitriding and Shot Peening Treatments and Stress Concentration on the Fatigue Strength of AISI 4340 Steel," SAE Technical Paper Series, Society of Automotive Engineers 2001-01-4070 E, 2001.
[13] Genel, K., Demirkol, M., and Capa, M., "Effect of Ion Nitriding on Fatigue Behavior of AISI 4140 Steel," Materials Science and Engineering, A279, 2000.
[14] Limodin, N., Verreman, Y., and Tarfa, T. N., "Axial Fatigue of a Gas-Nitrided Quenched and Tempered AISI 4140 Steel: Effect of Nitriding Depth," *Fatigue and Fracture of Engineering Materials and Structures*, Vol. 26, Blackwell Publishing Ltd., Malden, MA, 2003.
[15] "X-Ray Diffraction Residual Stress Analysis," Lambda Research, Rept. No. 400-11387, 24 Sept. 2003.
[16] Lindley, T. C., "Near Threshold Fatigue Crack Growth: Experimental Methods, Mechanisms, and Applications," *Subcritical Crack Growth due to Fatigue, Stress Corrosion, and Creep*, edited by L. H. Larsson, Elsevier Applied Science Publishers, New York, 1985.