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Fatigue Performance of Nitrided Aircraft Crankshafts

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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.

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].

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