

Load Carrying Capacity of Nitrided Gears

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ABSTRACT:

The pitting and bending strength of gas nitrided steel gears made of modified 39CrMoV13.9 (a 3% CrMoV type alloy) were investigated. Characteristics of the compound layer and the diffusion zone are examined. Residual stresses in the nitrided case are shown after long nitriding times. Bending fatigue and contact stress limits were very high, in the same order as case carburizing steels. For bending strength, additional damage line investigations were performed. From these results a comparatively poor overload tolerance has to be stated. The load carrying capacity of the modified 39CrMoV13.9 steel is discussed and compared with other carburized, gas, and ion nitrided gears.

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LOAD CARRYING CAPACITY OF NITRIDED STEEL GEARS

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The pitting and bending strength of gas nitrided steel gears made of modified 39CrMoV13.9 (a 3% CrMoV type alloy) were investigated. Characteristics of the compound layer and the diffusion zone are examined. Residual stresses in the nitrided case are shown after long nitriding times. Bending fatigue and contact stress limits were very high, in the same order as case carburizing steels. For bending strength, additional damage line investigations were performed. The load carrying capacity of the modified 39CrMoV13.9 steel is discussed and compared with other carburized, gas, and ion nitrided gears.

INTRODUCTION

Higher power density requirements often demand surface hardened gears. While carburizing is the most common and effective surface hardening method used to boost power ratings, the technique has shown substantial difficulties in the production of large gears. The quench hardening of hobbled gear rims from a high austenitizing temperature often results in unpredictable levels of tooth deflection, helix angle change, and overall distortion. Carburizing, therefore, is usually limited to smaller, solid pinions, while larger gears are often nitrided. Nitriding large gears has certain advantages. The low temperature used in nitriding and the absence of a quenching requirement assure minimal distortion. A post hardening treatment is not needed, and although profile grinding is required for better accuracy, metal removal is negligible compared to carburized or induction hardened gears. The high surface hardness of nitrided gears makes it possible to reduce diameter and center distance of mating gear pairs (and thus weight) resulting in a higher specific power density.

Large gears demand materials of high hardenability, and in the case of nitrided gears, materials with a good nitriding response. One such material is the German steel 39CrMoV13.9 (which is similar to a type 3% CrMoV steel). The steel's high alloy content assures good core hardenability as well as hardness in the nitrided case.

To assess the load carrying capacity of the modified (Mod.) 39CrMoV13.9 steel, a gear test program was conducted at the Gear Research Centre of the Technical University of Munich (FZG). The aim of the program was to generate fatigue data on the gear tooth bending strength and gear durability (pitting resistance) of this steel and to compare the results with other nitriding and carburizing steels. The overload tolerance of this steel in bending was characterized by damage line investigations. Further objectives of the program were to characterize the compound layer and diffusion-zone of the steel and to measure the residual stresses in the nitrided case after long nitriding times.

EXPERIMENTAL PROCEDURE AND RESULTS

MATERIAL AND GEAR CONFIGURATIONS -

The test gears were made from Mod. 39CrMoV13.9 steel forged bars. The chemical composition of the steel is shown in Table 1. The bars were cut and upset forged into blanks. The blanks were then normalized and hardened to two strength levels. The hardness and core tensile strengths (based on hardness) of the test gears after forging and heat treatment are shown in Table 2. Gear configuration and design parameters for the bending and pitting gears are listed in Table 3. The machined gears were nitrided by the ammonia gas nitriding process. Bending and pitting type test gears were nitrided separately at different times and to different case depths. The bending gears were nitrided to a minimum case depth of 0.94 mm (0.037 inches) to HRC 40, while the pitting gears were nitrided to a depth of

(0.027 inches). A nitriding time of 240 hours or more at a nitriding temperature of 540°C (1004°F) was required to achieve the case depth of 0.94 mm. About 150 hours were needed to produce a case depth of 0.69 mm. The hardness gradient of the nitrided case in two bending gears of different core hardness is shown in Figure 1. A typical microstructure of the nitrided case is shown in Figure 2, and details of the white layer are depicted in Figure 3. Precipitation reactions in the nitrided case after long nitriding times caused preferential carbide formation along prior austenite grain boundaries. X-ray crystallography showed the compound layer to be γ (Fe_4N) with no ϵ -phase ($\text{Fe}_{2.3}\text{N}$) present. Microprobe analysis showed the porous white layer to be rich in oxygen (oxides). The layer was quite soft (DPH 296-318) in comparison to the adjacent diffusion zone (DPH 772-802). Using x-ray diffraction techniques, the residual stress distribution in the nitrided case with increasing depth was determined in a gear tooth test coupon. The residual stress distribution had the form as shown in Figure 4. The surface exhibited moderate residual compressive stresses near the pitch diameter location and a relatively high residual stress at the root fillet. Low residual compressive stresses at the surface of nitrided Cr-Mo-V steels are apparently common after long nitriding times because of precipitation reactions occurring in the diffusion zone as was shown by Mittemeijer[1]. High compressive residual stresses were found below the surface with maximum values being at a depth of about 0.4 mm (0.015 in.). The flanks of the test gears were ground after nitriding. The tooth root area was left as heat treated.

BENDING FATIGUE TESTS - The bending fatigue tests were carried out on a mechanical resonance pulsator of 200 kN capacity. The frequency was 50 Hz. The gear teeth were clamped and loaded in such a way that the load direction was tangent to the base circle. The bending fatigue gear test set up is shown in Figure 6. A preload of 5 to 7 kN was used. The fatigue equipment is set up to make twelve separate tests on each gear. The endurance strength in bending was calculated by the DIN 3990[2] method.

The bending fatigue S-N curves for 50% failure probability of the Mod. 39CrMoV13.9 gears with two different core strengths are given in Figures 6 and 7. The curves are practically identical, with the lower core strength material showing a slightly higher endurance limit value at 5×10^6 load cycles (σ_{F_0} of 1020 MPa or 148 ksi versus 1008 MPa or 146 ksi, respectively). The fatigue endurance limit for this material is rather high when compared to other nitriding steels tested at FZG. The carbide banding in the diffusion zone and the presence of the white layer in the root area apparently did not have an adverse affect on the bending strength of the test gears. The rather shallow slope of the S-N

curve in the low cyclic regime and the presence of a noticeable "knee" in the S-N curve after a relatively short cyclic life (10^5 cycles) suggest a material which is prone to overload damage. Tests have shown that through-hardened, carburized, and induction hardened gears are relatively immune to overload effects. Their damage lines according to French[3] are generally close to and parallel to the S-N curves. Nitrided gears, on the other hand, have damage lines which typically deviate substantially from their S-N curves. Therefore, the material's performance under occasional overloads was investigated.

The damage line in bending fatigue of gears is obtained by initially determining the S-N curve and the endurance stress at 5×10^6 cycles for the alloy and nitriding condition and then subjecting a number of test gears to an initial overstress in the low cycle life regime (like 1000 to 3000 cycles) and then testing the gears at about 90% of the endurance stress to 5×10^6 cycles to determine whether or not damage by overstress occurred. If failure does not occur for this number of cycles, the overstress level in a new gear is raised for a predetermined number of cycles, and the gear is then again tested below the endurance stress. This process is repeated until failure occurs at less than 5×10^6 cycles. A series of such tests were performed on Mod. 39CrMoV13.9 bending fatigue gears at FZG. The results are shown in Figure 8. The squares in this figure represent the overstress and number of load cycles used in each test. The points connected with dotted lines to the same gear teeth indicate that failure occurs before 5×10^6 cycles when tested slightly below the endurance limit. The significance of the damage line for nitrided gear is this: Any combination of load and cycles within the field between the damage line and the S-N curve causes a decrease in the endurance limit. In the case of Mod. 31CrMoV13.9 steel gears any load higher than the endurance limit load causes a reduction of the endurance limit. The overload tolerance of the steel in bending, therefore, is very low.

DURABILITY TESTS (PITTING) - Durability or pitting endurance tests were performed on FZG gear test rigs shown in Figure 9. The gear center distance was 91.5 mm (3.6 inches). A detailed description of the test rigs is given by Winter and Michaelis[4]. The gears were lubricated by refined mineral oil ISI VG100 (viscosity $\nu = 100 \text{ mm}^2/\text{s}$ at 40°C (100°F) with a 4% sulfur-phosphorus additive. The pitting test gears were surface ground and were paired with carburized AISI 9310 gears. The nitrided gears meshed as pinions with the carburized gears. The gears were loaded to various Hertz stresses until failure occurred. An endurance limit was considered reached when the gears ran for 5×10^7 cycles without damage. A gear was assumed damaged when pits covered 1% of the total active surface of the