CORROSION FATIGUE OF POWDER FORGED STEELS

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The fatigue behaviour of a low alloy powder forged steel was investigated. Tests were carried out in air and in a 3% NaCl solution in water. To assess the influence of inclusions on the fatigue behaviour, the inclusion morphology was modified and some specimens were nitrocarburized. Fatigue cracks were invariably initiated from inclusions. Nitrocarburizing improved the fatigue limit about 40% in air and this improvement reached to 170% in the 3% NaCl solution in water.

INTRODUCTION

Powder forging is an attractive alternative to the conventional ingot casting and forging route for the production of certain engineering components. Among the advantages offered by the process are improved material utilization, close weight and dimensional tolerances, reduced machining, and improved surface finish.

Fatigue cracks in sintered parts have been observed to initiate at free surfaces, Haynes (1). Crack propogation is then aided by the linking up of pores. For fatigue resistance the inclusion content is of equal importance, Brown and Steed (2), Bockstiegel and Blande (3). With today's technology 99.99% dense products can be produced by powder forging. However, problems related to inclusions have not yet being solved, Sarıtas and Davies (4).

In the present paper the fatigue behaviour of a low alloy powder-forged steel is reported. The effects of inclusion distribution and environment on fatigue crack initiation have been carefully examined.

EXPERIMENTAL PROCEDURE

Material

The original powder was a Höganäs ATST-D powder which conforms to the GKN (GKN Group Technological Centre, Wolverhampton, England) W4 specification. It contained 0.07% carbon and 0.22% oxygen. All of the powder particles were smaller than 200 µm and the average particle size was 63 µm. Final carbon content of the forged blanks were adjusted by adding graphite powder before the cold consolidation operation. Graphite also worked as solid

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Table 1. Chemical composition of powder forged steels (wt %)

Material	C	S	P	Mn	Si	Ni	Cr	Mo	Cu	O_2
W4D	0.43	0.024	0.014	0.37	0.01	0.28	0.19	0.28	0.11	0.070
W4	0.45	0.024	0.014	0.37	0.01	0.28	0.19	0.28	0.11	0.015

lubricant during compacting. Cold pressing was carried out at about 300 MPa with die wall lubrication.

Two different preforging heat treatments were used to produce forged blanks with two different oxygen level. The compositions of the forged blanks are given in Table 1. The heated preforms were transferred quickly through a controlled atmosphere chute into the press and hot forged in a totally enclosed die set to 100% density with no lateral flow. The die set was maintained at about 250°C. After ejection following hot forging, the blanks were allowed to cool slowly by immersing in a sand bath. Blanks were 70 mm in diameter and 15 mm in height.

Testpiece Preparation

Three specimen blanks, 14 mm X 15 mm in cross-section, were cut from each forged billet. Quenching and tempering of the samples were carried out in this condition before further machining. The blanks were oil quenched at room temperature after austenitizing for 1h at 860°C in a muffle furnace and then tempered at 625°C for 1h. Tensile and rotating bending fatigue specimens were prepared from the blanks. The fatigue specimens were polished longitudinally to a 1 µm finish. Nitrocarburizing was carried out at 570°C for 3h duration in an atmosphere of 50% NH_3 and 50% endogas and then oil quenched to room temperature.

Mechanical Tests

Tensile testing was carried out at room temperature on an Instron machine at a cross-head speed of 0.2 mm/min.

Fatigue tests were carried out on a bench-type rotating bending (Wöhler) fatigue machine with a shaft speed of 2800 rpm. Specimens completing 10^7 cycles without fracture were classified as run-out speciments.

Hardnesses were determined by using a standard Vickers hardness tester with a 30 kg load. Microhardness profiles of nitrocarburized samples were obtained by employing a microhardness tester with a 50 g load.

Inclusion Counting

The area fraction of inclusions and their size distribution were determined by using a Quantimet 720 automatic image analyser.

The amount and distribution of powder particle boundary inclusions were measured by using two-stage plastic surface replicas.

Quantitative analysis of the inclusion compositions was carried out by examining polished metallographic specimens or fractured mechanical test specimens in a SEM with an energy dispersive analyser and a wavelength dispersive analyser.

EXPERIMENTAL RESULTS

Microstructure

As-forged metarials had a normalized structure, which up on heat treatment produced a tempered martensite and bainite structure. The nitrocarburizing treatment did not produce significant microstructural changes. A white compound layer was formed on the surface of the specimens which was roughly 15 µm. A microhardness profile of a nitrocarburized sample is shown in Fig.1.

Inclusion Distribution

The inclusions present in the steels have been classified as

(a) refractory inclusions : oxides of Mg, Ca, Ti and V.
(b) slag inclusions : Oxides of Al, Si, Cr, Mn, and Fe and sulphides of Cr, Mn and Fe.
(c) powder metallurgy inclusions : oxides of Cr, Mn and Fe.

In many instances some of the oxides in slag type inclusions were reduced to metal and a 'lacy' appearance was created.

The general inclusion distribution is given in Table 2. It is clear from the table that as the oxygen level was reduced from 700 ppm (in W4D) to 150 ppm (in W4), the area fraction of inclusions was reduced by 60%. An electron microprobe profile of an inclusion in W4D is given in Fig.2.

By a plastic replicating technique, carbides were also measured together with microinclusions. The calculated percentages of carbides were subtracted to obtain the microinclusion area fractions. A 78% reduction in oxygen content produced a 75% reduction in microinclusion area fraction.

Table 2. Inclusion Distributions in Materials

Material	Oxygen level ppm	Inclusion / mm² >10µm	>40µm	>100µm	Area Fraction %
W4D	700	21.0	1.5	0.05	0.35
W4	150	8.5	0.7	0.015	0.14

Table 3. Area Fractions of Carbides Plus Microinclusions in Materials

Material	Oxygen level ppm	Total area fraction(%)	Calculated carbides(%)	Inclusion area fraction(%)
W4D	700	14.3	6.46	7.84
W4	150	9.0	6.78	2.22

Mechanical Properties

These are listed in Table 4. Any change in UTS can be attributed to different batch of heat treatment.

The fatigue performance of the materials after each treatment, and in air or in 3% NaCl is represented in the form of S-N curves in Fig.3. The S-N curves and the last column of Table 4 show that the surface treatments improve the fatigue limit both in air and in 3% NaCl. Corrosion fatigue tests in 3% NaCl solution were only performed for W4 type material (150 ppm

Table 4. Mechanical Properties of Materials

Material	Condition	UTS MPa	Hardness (Microhardness)* HV	Fatigue Limit MPa
W4D	Quenched and Tempered	820	286	386 in air
	Nitrocarburized	-	(470)	552 in air
W4	Quenched and Tempered	864	296	441 in air 74 in 3% NaCl solution
	Nitrocarburized	-	(475)	579 in air 200 in 3% NaCl solution

*Microhardness of the compound layer.

oxygen level) since its performance was better. The reduction of oxygen level from 700 ppm to 150 ppm increased the fatigue limit only by 14%. In W4 material, nitrocarburizing increased the fatigue limit by 31% in air. The fatigue limit of nitrocarburized W4 in 3% NaCl solution is less than half of the value for the quenched and tempered condition in air. But if we compare fatigue limits in 3% NaCl solution, nitrocarburizing produced a 170% improvement.

Fractography

Fatigue cracks usually initiated at non-metallic inclusions and propagated rapidly ($>1\mu$/cycle). A typical fracture path was partly interparticular and partly transparticular. Secondary cracking at original powder particle boundaries was frequently observed. Fatigue striations were rare and those that were found were poorly defined.

In corrosion fatigue ; especially in quenched and tempered W4 specimens, heavy pitting corrosion was observed. There were micro-cracks associated with each corrosion pit. In nitrocarburized specimens however, minor pitting corrosion was observed. There were few microcracks at corrosion pits.

DISCUSSION

Reduction of Oxide Inclusions

An inherent disadvantage of the water atomization process for metal powder production is the inevitable surface oxidation of the powder particles. Atomized powders are annealed in a hydrogen rich atmosphere at temperatures below 1000°C. Annealing brings about a complete or partial reduction of those oxides which have a moderate free energy of formation, e.g., oxides of Fe, Ni and Mo. More stable oxides like oxides of Cr, and Mn remain virtually unchanged.

By emloying two different preforging heat treatments (coded by GKN) oxygen level of forged blanks were reduced from 2200 ppm to 700 ppm in W4D and 150 ppm in W4. Oxygen level in W4 is 78% lower than for W4D. Preferentially powder particle boundary inclusions were reduced (4), but as reduction continued, slag type inclusions were also reduced.

The oxygen level of W4D (700 ppm), and thus the inclusion content, is acceptable for industrial purposes. To determine the performance of powder forged steel at much lower oxygen levels, it is intentionally reduced to 150 ppm. At this oxygen level, oxides of Fe and Cr were almost totally reduced and oxides of Mn were partially reduced (4), Lindskog and Grek (5), Bastian (6).

Fatigue Properties

Changing the surface physical properties will obviously change the fatigue strength of an engineering component. Stronger and harder compound layers and/or cases produced by surface treatments will retard fatigue crack initiation at the surface, Forsyth (7), Coombs et al (8), Bell and Lee (9).

There is extensive experimental evidence (2,3), for example Duckworth and Ineson (10), Sumita et al (11) that the shape, size, amount, and chemical composition of inclusions all have an effect on the fatigue properties of materials. Any treatment which can alter anyone of the above variables can produce a change in fatigue properties. It is generally agreed that inclusions play an important role in crack initiation. Duckworth and Ineson (10) mentioned a critical size of inclusions above which a detrimental crack will definitely initiate from inclusions. Their work shows that, with failures which originate at the surface or just below the surface, the critical inclusion size in 10 μm. When the origin of failure is more than 100 μm below the surface, the critical inclusion size is 30 μm. A reduction in oxide inclusion content (inclusions > 10 μm) by 60% produced a 14% improvement in endurance limit in air. Fractographic examinations revealed that different types of inclusions affect the fracture behaviour in significantly different ways, Sarıtas and Davies (12). In W4 material, refractory inclusions had a dominant effect on fracture whereas in W4D material the 'lacy' slag inclusions were more frequent on the fracture surface. This occurs because the big slag-type inclusions which were frequent in W4D were reduced to smaller inclusions in W4.

The fatigue limit value was reduced by 83% for quenched and tempered condition in 3% NaCl solution. This reduction is 65% for nitrocarburization treatment. It is quite clear that nitrocarburization treatment could not stop pitting corrosion but it slowed down it. Although failures around 10^6 cycles were very rare in air tests, due to continous corrosion and deterioration of surface properties, failures around 10^7 cycles were quite frequent in 3% NaCl solution tests. Low cycle fatigue failure parts of the S-N curves for 3% NaCl solution tests were coincided with air values since there was no time for corrosion to take place. Although nitrocarburization treatments could not stop pitting corrosion, compared to quenched and tempered condition, it produced a performance that was 170% better.

CONCLUSIONS

1. Reducing the oxygen content by 78% produced only 14% improvement in the fatigue limit.
2. Nitrocarburization increased the fatigue limit by 43% for a 700 ppm oxygen level in air and by 31% for a 150 ppm oxygen level in air. Nitrocarburization supressed inclusions in the material with 700 ppm oxygen.
3. 3% NaCl solution reduced the fatigue limit very considerably. Nitrocarburization slowed down corrosion but could not stop it.

4. Nitrocarburization treatment produced a performance 170% better than quenching and tempering treatment in 3% NaCl solution.

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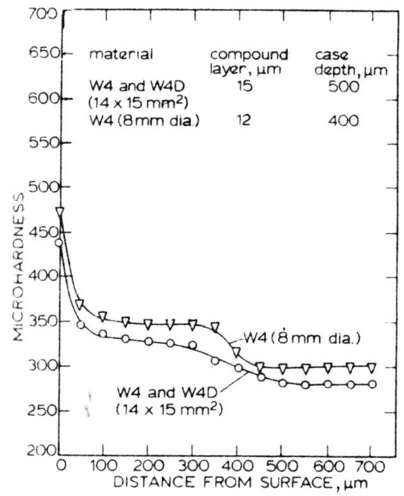

Figure 1-Microhardness profile of a nitrocarburized material.

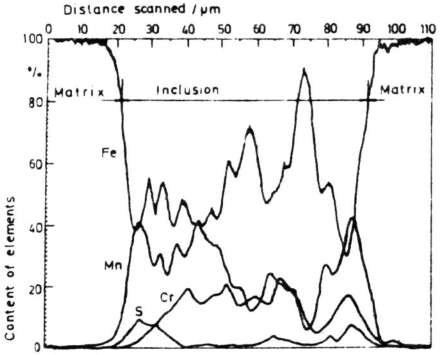

Figure 2- Electron Microprobe Profile of an Inclusion in W4D.

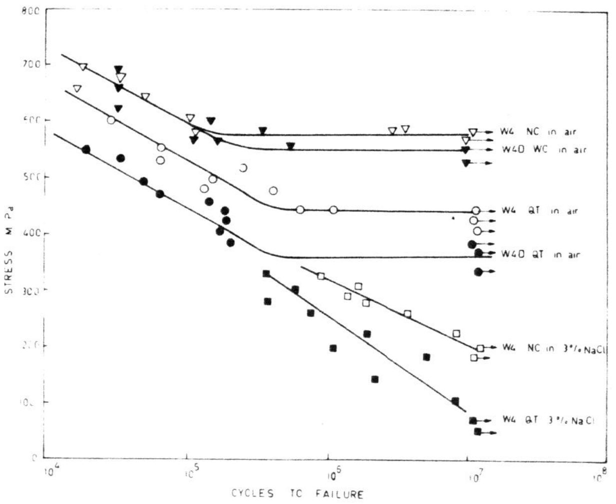

Figure 3- S-N Curves of Material After Different Treatments Under Different Environments.