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Review

Duplex Hardening of Steels for Aeroengine Bearings

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Duplex hardening is a process in which conventional heat-treatments such as secondary or case hardening are followed up by surface nitriding to achieve exceptional properties, particularly in the context of aeroengine bearings. Hardness values in excess of 1 000 HV can in principle be achieved, and although the hardness decreases as a function of depth below the surface, some level of enhancement can occur to a depth of up to 0.2 mm. The process can be applied to both through hardened and case hardened bearing steels such as M50 and M50NiL respectively, with concomitant increases in rolling contact fatigue resistance and tribological properties. The process has not yet been universally adopted and is ripe for a critical assessment.

KEY WORDS: duplex hardening; nitriding; case hardening; bearing steels.

1. Introduction

Aircraft engines represent the pinnacle of engineering excellence with many components that must operate reliably in difficult circumstances that stretch the limits of material capabilities. Bearings on engine shafts have to tolerate vibratory stresses, bending moments and high rotation speeds, for example, 25 000 revolutions per minute, elevated temperatures and aggressive lubrication. They generally are made using steels designed to resist rolling-contact fatigue, wear by a variety of mechanisms, and to maintain structural integrity. However, the most commonly reported failures are due to surface-initiated damage rather than due to subsurface stresses induced during rolling-contact.1–3) The duplex hardening process which is the subject of this review deals precisely with the enhancement of surface properties and hence is particularly relevant to aeroengine bearings.

Duplex hardening[1] involves the application of a thin nitrided layer to bearing components which have already been given a conventional hardening treatment; the latter refers to either a through-hardened steel or one which has been case-hardened following carburisation.3–7) Secondary hardening[2] of the component is necessary, since it is essential to attain the proper hardness before the start of the nitrding process. The goal is to achieve a superior tribological resistance through an increased surface hardness, and possibly by the raising the level of compressive residual stress in the region near the surface.3)

Given a requirement for hardness at elevated temperatures, two of the popular steels used in the manufacture of aeroengine bearings are intermediate high-speed tool steels designated M50[3] and M50NiL[4], with typical chemical compositions as listed in **Table 1**. M50 is a secondary-hardening steel which is quenched to generate martensite and then tempered 540–550°C in order to precipitate a combination of alloy-carbides rich in molybdenum, chromium and vanadium;8–10) the actual heat treatment can be quite complex in order to control the retained austenite. M50NiL is a derivative which is used in a case-hardened condition with a relatively tough core. The hardness of the approximately 0.75 mm deep case11) then matches that of the through hardened M50, at about 60–64 HRC (740–840 HV). Details of

Table 1. Approximate chemical compositions in wt%. The last two alloy compositions are included for discussion purposes.

	C	Si	Cr	Mo	V	Ni	Mn	
M50	0.83	0.25	4.1	4.25	1.0		0.2	
M50NiL	0.13	0.18	4.1	4.25	1.2	3.5	0.2	
52 100	1.0	0.2	1.45				0.35	
M2	0.92	0.32	4.10	5.0	2.0	0.3	0.2	W6.2

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[1] The term 'duplex hardening' is used since there are two hardening processes involved: a) the secondary hardening and b) the surface hardening process (nitriding).

[2] Secondary hardening is commonly referred to a tempering process of steel that result in greater hardness, mainly due to the precipitation of stable carbides. In this particular case, the retained austenite, which affects the dimension stability of the component, is also eliminated.

[3] 'M' in M50 indicated that the steels that have molybdenum additions as one of the primary alloying elements. M50 also has other names in different standards, which included UNS T11350, EN 10027-2/WL 1.3551, AISI M50, AIR: E 80DCV40, B60 in ISO 683-17 and 80MoCrV42-16. Standards concerning the production of the steel are AMS6490 and AMS6491.

[4] M50NiL has the same chemical composition as M50 with lower carbon content and nickel addition. The 'Ni' in the name is stands for nickel while 'L' means low carbon. Others name of M50NiL included AMS 6278 and G13Cr41704Ni4V.

the physical metallurgy of these alloys are available in recent reviews so are not repeated here[10,12] but it is useful to show some of the relevant properties. **Figure 1** shows data for both the M50 and M50NiL steels; of particular note is that the residual stress profile in the vicinity of the surface and to depths where rolling contact damage might be focused is particularly favourable for the latter alloy. This is because the case carburisation process itself introduced compressive stresses; when the component cools from the austenitic condition, the surface cools at a faster rate than the interior, and hence relaxes by plastic deformation. However, martensite eventually forms within the carburised region, and the associated transformation strains lead to an expansion of the surface relative to the non-transforming core, thus leaving it in compression. With M50, the state of the stresses in a shallow surface region is determined by the finishing operations, for example grinding and honing.[11,13,14] The data illustrated in Fig. 1 will be modified by the addition of a nitriding process during manufacture, as will be illustrated later in the review.

2. Duplex Hardening: The Process

To achieve the introduction of nitrogen by diffusion into a steel over a reasonable time scale requires heat treatment at temperatures in excess of 500°C. Substitutional solutes and iron atoms also have significant mobility at such temperatures so only those alloys whose properties are not influenced by the tempering experienced can be considered for nitriding. Both M50 and M50NiL are secondary hardened as illustrated in **Fig. 2**[15] and hence are amenable to nitriding heat treatments. We now discuss the variety of nitriding processes that have been used for these aeroengine alloys.

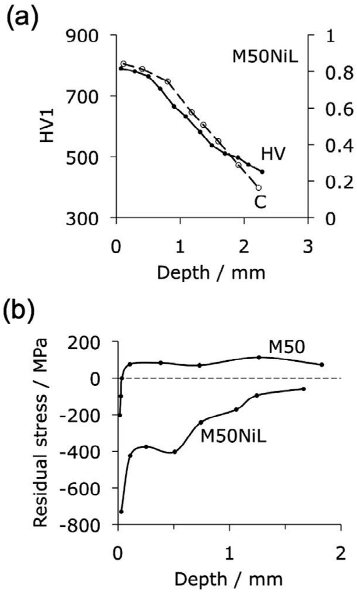

Fig. 1. (a) Hardness and carbon concentration as a function of depth for a case-hardened M50NiL steel. (b) Residual stress variation as a function of depth. Data from.[11]

2.1. Salt Bath Nitrocarburisation

The nitrogen in this case comes from a molten salt mixture of cyanide (a compound of C, N) and cyanate (C, N, O). This is the reactive compound which catalytically decomposes on the steel surface, at elevated temperatures in the range 550–590°C, to produce a cyanide (C, N).[16] Both carbon and nitrogen diffuse into the steel, but the very surface becomes rich in nitrogen to precipitate an outer layer rich in ε-iron nitride (Fe_2N_{1-x}),[17] beyond which there is a diffusion layer.[18] The white coloured ε layer can be detrimental because the phase is brittle. A disadvantage of salt bath treatment of this kind is the toxic nature of the salt, so that the process is increasingly being substituted by gas or plasma nitriding.

2.2. Gas Nitrocarburisation

This process is usually performed in a stream of ammonia (NH_3) gas at atmospheric pressure in a furnace or fluidised bed. The catalytic decomposition of ammonia provides the required active nitrogen, which is able to diffuse into the steel. Nitrogen and hydrogen are also used as additives, while gases such as carbon dioxide, methane or carbon monoxide are used as sources of carbon.

Gas nitrocarburisation using fluidised bed furnaces, and its implications on the properties of both M50 and M50NiL has been studied since the early 1990s;[15,19,20] the furnace gas used had equal amounts of methane and ammonia. The formation of the white layers at grain boundaries was avoided by implementing a short treatment time (maximum 16 h at 524°C)[5]. **Figure 3** shows the effect of treatment time on the ε-nitride and diffusion layer thickness during ferritic nitrocarburising. M50NiL is able to absorb nitrogen to a greater depth than M50. The reasons for this are not understood. M50NiL has a slightly larger concentration of vanadium which is a strong nitride-forming alloying element (Table 1), but this would tend to reduce penetration by precipitation of nitrides.[21] There is also no clear evidence in the literature about the role of nickel on the kinetics of nitriding; on the contrary suggestion that at large nickel concentrations, the nitriding of austenite in FeNiN alloys is much slower than FeN.[22] Figure 3 also shows that the time required to achieve a given diffusion layer thickness can be reduced by using a different gas mixture and a slightly greater process temperature. An alternative gas mixture of 25% ammonia in hydrogen has also been used to nitride M50,[6] but requires a long treatment time (60 h at 500°C), and the precipitation of white compound on the grain boundaries has been reported.

2.3. Plasma Nitrocarburising and Nitriding

Plasma nitriding is also known as ion or glow nitriding. It involves the addition of nitrogen and/or carbon to ferrous materials in a selective gas mixture environment using a low-energy plasma. The supply of the nitrogen is through an ionised gas mixture consisting of nitrogen, hydrogen and an additive gas containing carbon, such as methane or carbon dioxide. The components to be nitrided are connected to the cathode of the plasma generator. Additional heating is some-

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[5] It should be noted that the maximum nitriding temperature is usually determined by the need to avoid softening the secondary hardened state of the steel; the temperature should therefore be less that that used during tempering, *i.e.*, below 540–550°C.

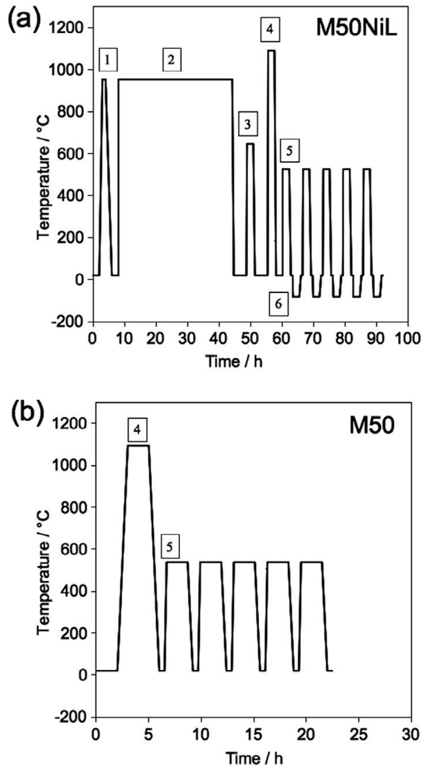

Fig. 2. Typical heat treatments for M50 and M50NiL steels.[15] The numbers in squares have the following meanings: 1) oxidation, 2) carburising, 3) stress relief, 4) solution treatment and quenching, 5) tempering, 6) sub-zero cooling.

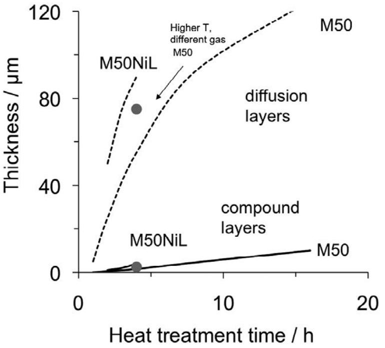

Fig. 3. Effect of nitrocarburising time at 524°C on compound and diffusion layer thicknesses. The experimental results marked as circles represent a different gas mixture of ammonia, endothermic gas, air, carbon dioxide and hydrogen and a higher temperature (538°C). Data from.[20] The M50NiL was nitrided after case hardening.

times applied to avoid thermal gradients within the components.

In plasma nitriding ionised nitrogen atoms bombard the surface and diffuse into the interior of the work pieces. This enables the nitrogen to penetrate the metal substrate rapidly, and at lower temperatures than other nitriding reactions. Once the nitrogen has entered the surface of the metal it progresses to the subsurface regions by diffusion, although the process is complicated by the formation of the compound layer and indeed, any precipitation of carbon or nitrogen further into the depth of the material.

A gaseous atmosphere in the ratio of 2% N_2 and 98% H_2 and at a pressures of 1–3 torr is suggested in a patent for plasma nitriding both M50 and M50NiL.[23] The claimed temperatures and times in that patent are 375–592°C and 1–2 h, thus avoiding the formation of the compound layer. This has the advantage that the component need not be ground following the plasma nitriding process. The reported surface hardness achieved was 900–950 HV for both M50 and M50NiL.[24] For example, in other work[6] involving nitriding at a temperature of 500°C and a longer time 40–70 h, a final grinding process is needed to eliminate the compound layer.

Plasma nitriding using a mixture of equal amounts of nitrogen and hydrogen has been practically achieved at 430°C and 10 h.[25] After cooling to ambient temperature, the nitrided components were placed in a furnace at 430°C for 160 h in order to allow the interstitial elements to penetrate further into the depth of the M50 and M50NiL steels. It is noted that the components were cleaned using argon sputtering prior to the nitriding treatment.

Of the three reported nitriding processes, plasma nitriding is the fastest compared with salt bath or gas nitriding and allows a lower treatment temperature for a short duration. It also avoids the use of ammonia which some consider to be an environmental advantage.[25] The relatively smaller consumption of gas is a further advantage of the plasma process.

2.4. Partial Pressure of Nitrogen and Carbon

The partial pressure of nitrogen gas must clearly affect its absorption and diffusion into the metal since there must exist a tendency towards local equilibrium for nitrogen at the metal-gas interface. A rate of nitrogen absorption greater than that of diffusion would lead to an increase in the concentration at the surface of the steel, possibly to a level that stimulated compound-layer formation and intergranular precipitates. It has been claimed in a patent that the ideal nitrogen concentration required to avoid intergranular precipitates is below 1.80 wt%.[26] However, it is known that the level of carbon in the steel being nitrided can influence the critical nitrogen concentration; a combined value of carbon and nitrogen of 1.7 wt% is suggested to avoid detrimental precipitation effects.[25]

Some carbon source in the gas mixture seems also to encourage the penetration of nitrogen into the substrate, so a thicker diffusion layer can be obtained and decarburisation effects avoided. Rhoads claimed that the presence of carbon during nitriding acts to prevent the decarburization of the steel,[26] although others suggest that carbon tends to promote the formation of grain boundary precipitates.[27,28]

3. Structure and Hardness

3.1. Layered Structure in Nitrided Zone

Figure 4 shows a schematic cross section of nitrided layer. The surface zones of the nitrided metal are macroscopically composed of two distinct parts, directly at the surface is the compound layer which has an intrinsic white colour (not simply white-etching), is hard and chemically resistant. Beneath the compound layer is the tougher nitrogen-rich diffusion zone. The compound layer can exist as one of the three following forms, depending on the depth and distributions of nitrogen and carbon: ε-$Fe_2(C,N)_{1-x}$, γ'-Fe_4N phase or a mixture of both. Both these phases are characterised by high hardness, high resistance to wear and corrosion resistance but at the same time, are brittle.

The implication of this compound layer on rolling contact fatigue has been investigated for both M50 and M50NiL by Braza and Pearson.[20)] While it has been claimed by many investigators that the presence of the compound layer has an adverse effect on rolling contact fatigue, it is clear from **Fig. 5**[20,29)] that a thin compound layer can be beneficial when compared to untreated specimens. The optimum compound layer thickness for maximum fatigue life for the circumstances of those tests is about 0.5 μm for M50; *i.e.*, tests conducted on a ball-on-rod tester[30)] with a very high contact stress of 5.43 GPa and a specific lubricant.

It is suspected that under cyclic loading, cracks form more readily in the thicker compound layers (>2 μm), which then serve as initiation points for the propagation of fatigue cracks. Therefore, controlling the thickness of the compound zone through nitriding time or removing the compound layer by grinding should optimise the rolling contact fatigue performance.

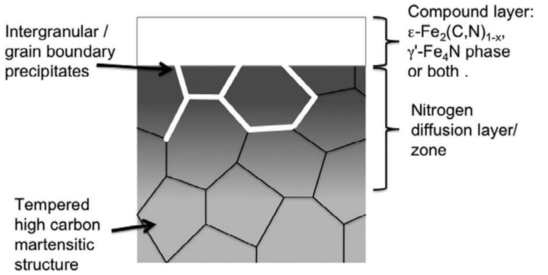

Fig. 4. Schematic cross section of a typical nitrided layer before the compound layer is removed.

An analysis of the fatigue life obtained by Braza and Pearson[20)] in Figs. 5(a), 5(c), show that there is no significant improvement of fatigue life between short term nitriding with a 0.5 μm thick compound layer as compared with long term nitriding with compound layers removed by grinding in M50. However, the fatigue life of M50NiL showed a marked improvement when thick compound layers were removed by grinding following the long nitriding treatment.

Figure 6 shows a typical cross-section microstructure obtained in duplex hardening M50NiL after the compound layer is removed. Right beneath the surface is the nitrogen rich diffusion zone, depending on the nitriding process, this layer is typically 100–150 μm in thickness. It is found that the nitrided region appears to be depleted in carbide precipitates (Fig. 6(a)), which appear light as observed deeper within the sample. Similar observations have been reported on other steels,[31,32)] with the suggestion that the introduction of nitrogen destabilises the carbides formed during tempering and that these carbides were replaced by the precipitation of smaller and more stable nitrides. The liberated carbon is then able to diffuse inwards and re-precipitate as fine carbides (Fig. 6(b)). This carbon can also diffuse outward taking part in the formation of compound layer. Below the nitrogen-rich zone is the carburization layer, in which the intergranular and intragranular carbides that form after tempering of high carbon martensite are observed, with the amount of carbide decreasing with depth (Figs. 6(c)–6(e)). The low carbon martensitic microstructure of base metal of M50NiL is shown in Fig. 6(f).

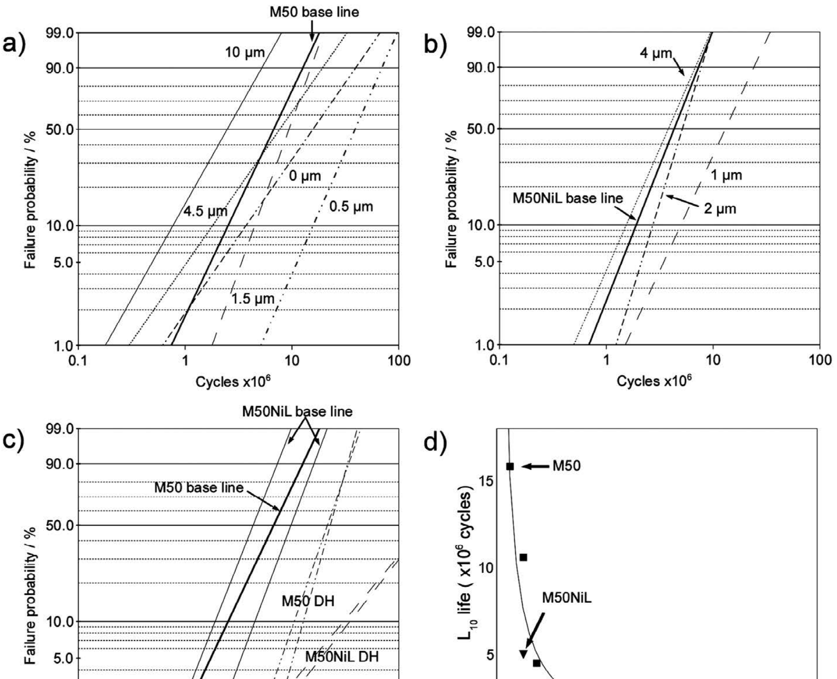

Fig. 5. Effect of compound layer thickness on rolling contact fatigue for both M50 and M50NiL. a) M50 steel. b) M50NiL. c) After the compound is ground. d) L_{10} life of duplex hardened test specimens against compound layer thickness. After.[20,29)]

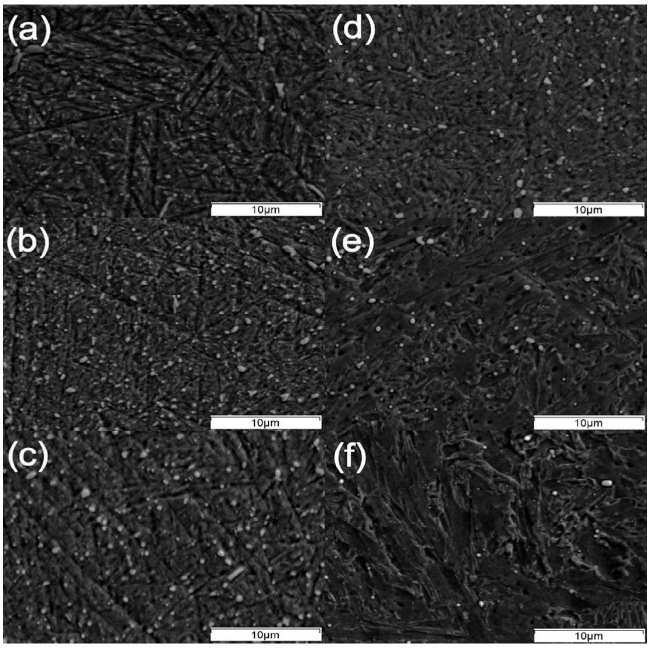

Fig. 6. Nitrogen diffusion zone: (a) Beneath the surface, (b) 0.1 mm from the surface, Carburization layer: (c) 0.5 mm, (d) 1 mm, (e) 1.5 mm, Martensitic microstructure of M50NiL based metal: (f) 2 mm.

3.2. Optimum Hardness Profile

The hardness profile of nitrided components depends on their alloy composition, nitrogen potential, process temperature and time, as well as the voltage experienced during the plasma process. **Figure 7** illustrates the hardness profile of M50NiL after plasma nitriding.[6,24,25,33] The hardness achieved with the higher nitriding temperature and nitrogen potential is, as might be expected, greater, given the higher likelihood of intragranular precipitation (Fig. 4).[33] In order to avoid this intergranular precipitate, a low temperature and low nitrogen potential has been preferred by other workers.[6,24,25]

It has been claimed[23,24,34] that both M50 and M50NiL can be plasma nitrided to a depth of 150 μm without compound layer formation, while achieving a surface hardness of about 1 100–1 250 HV (**Table 2**). It is also suggested in that claim that the optimum depth for the improvement of rolling contact fatigue using nitriding is between 100–150 μm. The benefit of the proposed short treatment time not only prevents the formation of a compound layer and the grain boundary precipitates, but also saves on grinding costs and increases productivity.

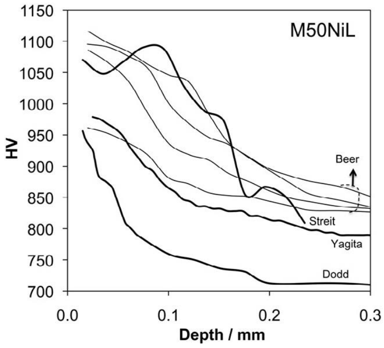

Fig. 7. Hardness profiles of M50NiL after plasma nitriding reported by various workers. After.[6,24,25,33]

Table 2. Improvement in rolling contact fatigue (RCF) in relation to the depth of hardened surface layer due to plasma nitriding of M50NiL.[23]

Depth/μm	Hardness/HV0.3	Improvement in RCF
Untreated	700–750	×1
25	850–900	×3
50	900–960	×4
75	940–1 000	×4
100	1 000–1 150	×5
150	1 100–1 250	×5
200	1 100–1 250	×4

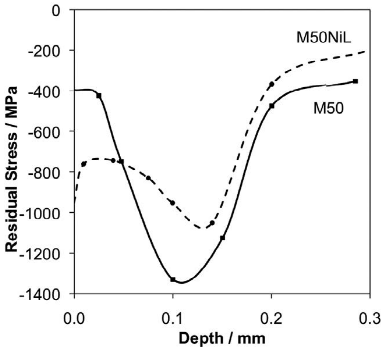

Fig. 8. Residual stress profile of M50 and M50NiL after duplex hardening.[6]

4. Residual Stress

The introduction of residual stress which places the surface into compression is an additional benefit of the nitriding process designed for hardening; this must clearly be beneficial to rolling contact fatigue resistance;[35] it is known that such a stress in M50NiL extends the RCF life.[36] This combination of mechanical properties associated with the process improves the resistance to damage initiation. **Figure 8** shows the measured residual stress profile near the surface after nitriding in both M50NiL and M50,[6] where there is a locked-in compression in the vicinity of the surface. Similar results have been reported by others.[37–39] The compressive stress is a consequence of the change in the chemical composition of the diffusion zone, formation of nitride precipitates and the difference in the thermal expansion coefficients of the nitrides and the ferritic substrate during cooling.[35]

5. Effect of Alloying Elements

Alloying elements such as chromium, vanadium and molybdenum are present in both M50 and M50NiL, and have a significant influence on the attainable hardness and the depth of the diffusion layer during nitriding. Chromium and vanadium in particular tend to precipitate as fine nitrides in the diffusion zone, resulting in precipitation hardening. While no systematic investigation seems to have been made, CrN, MoN and V_2N are expected judging from experimental data on nitrided M2 steel.[37] Nitrogen atoms in solid solution within the diffusion zone may also contribute to hardness through solution hardening or by interfering with dislocation mobility. The influence of these elements on hardness obtained after nitriding is shown in Fig. 8.37)

6. Distortion and Dimensional Change

The absence of an allotropic phase transformation during duplex hardening results in minimal overall distortion, although compound formation, precipitation and the incorporation of solute does lead to a slight though significant growth in volume. As stated in section 4, such changes are responsible for the development of a compressive state of residual stress in the vicinity of the component surface. The dimensional change due to nitriding of the raceway rings of both M50 and M50NiL has been characterised;15) the outer diameter for both M50 and M50NiL rings grew about 0.0762 mm from a starting diameter of 640 mm after nitriding at 524°C for 32 h, attributed in part to the nitrogen-rich white layer that formed on the surface.

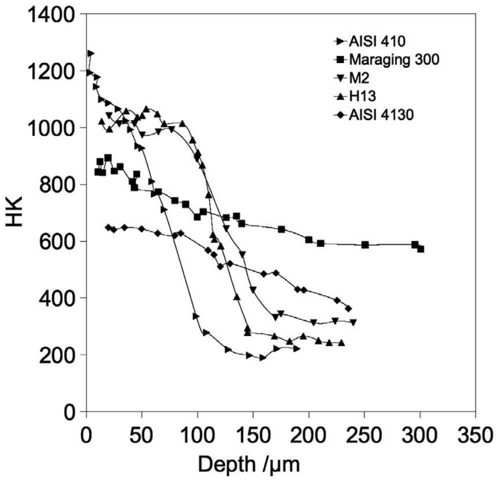

Fig. 9. Knoop hardness (HK) profiles for a variety of steels after plasma nitriding for 9 h.37) The chemical composition of the steels is shown in **Table 3**. This kind of a microscopic hardness test utilises an elongated indent, which is shallow relative to a Vickers indent, in order both to deal with more brittle materials and give a greater spatial resolution along one direction.

Table 3. Chemical composition (in wt%) of steels quoted in **Fig. 9**.

	AISI410	H13	M2	Maraging 300	AISI4130
C	0.15	0.40	0.85	0.03	0.30
Si	1.00	1.20	–	–	0.20
Mn	1.00	0.40	–	–	0.45
V	–	1.00	–	–	–
Mo	–	1.40	–	–	0.20
W	–	–	2.00	–	–
Cu	–	–	5.00	–	–
Ni	–	–	6.00	18.00	–
Co	–	–	–	9.00	–
Ti	–	–	–	0.90	–
Al	–	–	–	0.10	–
Cr	12.50	5.30	4.00	–	1.00

7. Final Grinding

A finish-grinding process is needed to remove any thick compound layer that forms, which can be detrimental to mechanical properties (Fig. 5). Grinding after nitriding is common, although there are two reports20,25) where the additional process was considered unnecessary. If the main objective of duplex hardening is to improve surface properties rather than subsurface properties, deep nitriding may not be essential to improve bearing reliability. Plasma nitriding can then be used to produce a simple diffusion layer24) without the need for the final grinding process. Moreover, the rolling contact fatigue properties will not be compromised as long as compound layer less than 1 μm in thickness.20) The grinding part of the manufacturing process can be eliminated if the bearing dimensions can be adequately controlled during nitriding.

While the white compound layer can be removed, both M50 and M50NiL are also prone to the formation of intergranular nitrides precipitating at the prior austenite grain boundaries. Such nitrides can adversely affect the rolling fatigue life of a bearing increasing the chance for spalling.25,26) However, others have claimed that the presence of a fine intergranular nitride network does not affect the fatigue life.15) Further work is needed to evaluate the limits of the effects described.

8. Bearing Fatigue Life Evaluation

The reported change in rolling contact fatigue life due to duplex hardening is evaluated relative to the unmodified specimen. Since there is no standard for measuring the rolling contact fatigue life, the test rigs used and the contact stresses imposed can vary widely. The test rigs reported in the literature included a three ball tester designed by Federal-Mogul Corporation30) used by Torrington Company,20,29) a double roller rolling fatigue tester,24) an 'L17' test rig3,33) and Polymet.24)

To induce failure in a reasonable timescale, large Hertzian contact stresses are used (2.5–5.42 GPa), whilst the contact pressure in actual application of aeroengine bearings is usually less than 2 GPa. It is expected that the high contact stress will produce considerable plastic deformation and subsurface metallurgical alteration in the specimens causing damage not typical of that observed in service. Having said that, as shown for example in **Fig. 10**, the rolling contact fatigue tests performed in all reported literature indicated superior performance of duplex hardened M50 and M50NiL over corresponding unmodified bearing components. To mimic the worst-case scenario during bearing operation, the testing conditions reported in the literature include boundary lubrication conditions,3,6,20,24,29) and sometimes the introduction of artificial indentations in the rolling contact zone.6,40) Duplex hardening of M50 balls performed by Beer33) also shows favourable test results.

9. Resistance to Wear

The bearing surface will not be subjected to wear if the surface finish and the lubrication conditions are adequate, although this is unlikely to always be the case during the

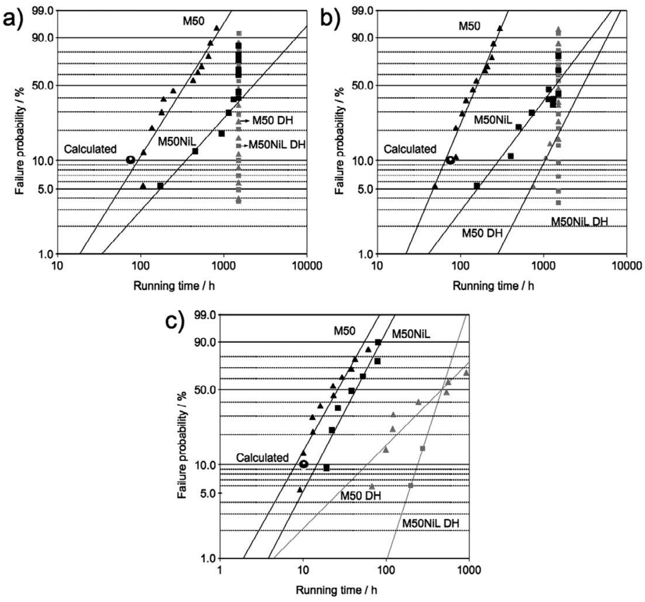

Fig. 10. a) Bearing life test results under boundary lubrication with Hertzian contact stress of 2 500 MPa.6) b) Bearing life test results under elastohydrodynamic lubrication conditions and artificial indentations in the rolling contact zone with Hertzian contact stress of 2 500 MPa.6) c) As in (b) but with Hertzian contact stress of 3 050 MPa.40)

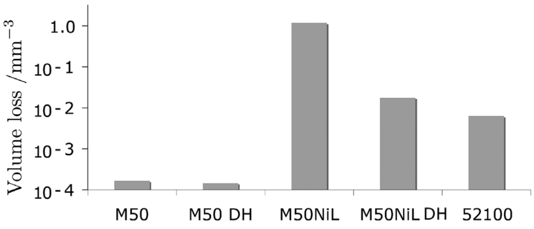

Fig. 11. Reported volume loss after sliding wear test of M50 and M50NiL with and without duplex hardening against M50. Test result on 52 100 steel is also included. After.20)

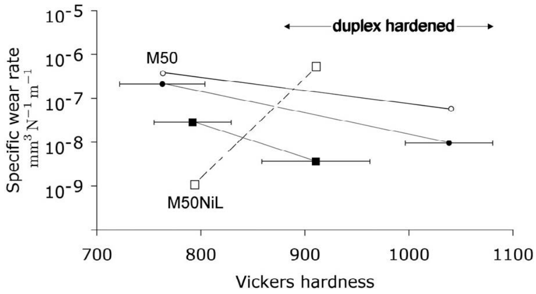

Fig. 12. Pin (silicon nitride) on metallic disc tests for through-hardened M50 (circles) and case-hardened M50NiL (squares), with corresponding data for the duplex hardened condition. Data from.43) The filled points represent tests with a load of 60 N, whereas the open circles involved a load of 120 N.

course of bearing operation. Lubrication may fail or its contamination by particulate debris created either by separation from the bearing itself or a foreign source will cause wear.10,41) Wear will also occur when there is microscopic slip between the rolling pairs. Sliding contact can happen when the applied loads and speeds change abruptly. The resulting damage gives rise to stress concentrations, exacerbating localised plasticity, interrupting lubricant film formation and ultimately reducing bearing life. It has been known for some time that in unlubricated sliding wear tests, nitrided steel not only exhibits a reduced wear rate but can tolerate much greater loads and sliding speeds before the onset of what is classified as severe adhesive wear.42) The reduced wear rate is not surprising since in the context of aeroengine bearings, the typical surface hardness of M50 and M50NiL is about 750 HV whereas the corresponding nitrided surfaces can exceed hardness values of 900 HV.43)[6]

The wear resistance associated with duplex hardening clearly can help in these circumstances so the process has been applied to M50NiL19,20,44) as shown in **Fig. 11** which represents metal against metal tests.45) However, only a minor change is observed in the case of M50 steel which in any case has an intrinsically low wear rate. The inferior wear resistance of M50NiL can be attributed to the lack of large carbide precipitates compared to M50.46) The significant effect of large carbide on wear resistance can also be observed when M50NiL and 52 100 were compared, where it is observed that the latter has a smaller volume loss when against M50 steel in a sliding wear test.20) This particular test19,20,44) where another bearing steel is rubbed against a test sample is a popular experiment in assessing the wear resistance. However, due to the high rubbing forces used, it is possible that the wear mechanism and damage is not identical to that experienced in service.

In contrast, for during pin-on-disc tests using silicon nitride pins on metal,43) tests carried out using a load of 60 N corresponding to a pressure of 2.5 GPa showed significant improvements in the specific wear rates of both M50 and M50NiL in the duplex-hardened condition (**Fig. 12**). This remained the case for M50 when the load was doubled, but for reasons which are not explained, the case-hardened M50NiL showed an anomalously low wear rate and the duplex-hardened M50NiL a very high wear rate, there may have been a change in wear mechanism but these results deserve to be verified.

10. Resistance to Spall Propagation

Once damage has blemished the surface, further material may be removed from the bearing as it spalls. Streit and colleagues40) conducted delicate experiments where spall propagation on M50NiL bearing raceways and its duplex-hardened variant was investigated. **Figure 13** shows the spall area measured at an intermediate stage of laboratory bearing testing. The initial spall was introduced by the same bearing test. Duplex hardening helps resist spallation during the continued running of the bearing, where the spall area remains small in spite of a long running time.

11. Hybrid Bearing

The use of hybrid ball bearings, consisting of steel races and ceramic balls (Si_3N_4) is now prominent in applications where the rotation speed is very large, for example in aeroen-

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[6] This assumes that extremely brittle phases such as the compound layer are absent or thin enough to avoid cracking.

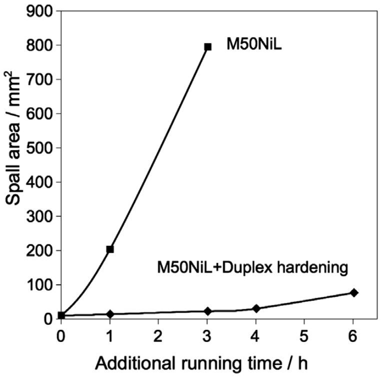

Fig. 13. Spall propagation of M50NiL versus M50NiL after duplex hardening.[40]

gines and in some manufacturing equipment. The silicon nitride is hard (76–80 HRC) and has a density (3.27 $g\ cm^{-3}$) which is much lower than that of steel.[47] Its large elastic modulus (310 GPa) leads to a small contact area which in one sense is an advantage if it leads to less microscopic sliding. However, the fracture toughness of the ceramic can be a problem with rapid rolling element crumbling initiated by surface damage under continued operation. This means that the failure detection is a particularly important consideration in critical applications such as aeroengines. Duplex hardened M50NiL race rings have been made for use with ceramic balls made from silicon nitride (Si_3N_4).[15] It is reported that the rolling contact fatigue performance of hybrid ceramic/duplex hardened steel bearings is far superior to conventional M50 and M50NiL steel bearings.[15]

12. Summary and Comments

There is no doubt that duplex hardening increases bearing life under overloaded testing conditions, indicating that the additional process will be beneficial in improving aeroengine reliability, especially in circumstances preceding gross damage. The primary attribute of the nitrided surface is the increase in surface hardness accompanied by the increase in strength and the generation of compressive residual stresses in the near-surface layer. This beneficial combination provides more resistance to spallation and the robustness to surface damage.

However, there remain a few metallurgical queries, as there is a need to evaluate the effect of intergranular nitrides (white compound) on rolling contact fatigue as the reported results contain contradictions. The wear mechanism of duplex hardened M50NiL with high loads in pin-on-disc tests need to be examined in order to reveal further information on the mechanism of wear.

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