Deep Nitrided 32CrMoV13 Steel for Aerospace Bearings Applications

Daniel GIRODIN*

Bearings for aerospace applications such as main shafts of jet engines need to be extremely reliable in order to reduce the In Flight Shut Down (IFSD) ratio and extend the frequency of maintenance operations. These functional and economic issues require for the material the implementation of appropriate and reliable metallurgical solutions.

This report describes the developments of the nitriding 32CrMoV13 steel (AMS 6481) to optimize its properties in order to overcome the limits of classical steels used for aeronautical applications, such as resistance to surface damage and toughness. The deep nitriding provides a case deeper than 600 µm, a high surface hardness in the diffusion zone due to a semi-coherent precipitation of nano-metric chromium nitrides. This precipitation also generate compressive residual stresses, while maintaining a notably high tough core. These properties offer considerable advantages in extending both the surface resistance to contamination and the ability to design bearings with integrated design and thin sections that consequently reduce the weight of components.

1. Introduction

Bearings for aerospace applications operate under severe service conditions and have been a continuous challenge from the material point of view over the years. Bearings for aircraft turbine engines are required to operate at high speed and temperature, while bearings for helicopter transmission gearboxes require high load capacity. These conditions are combined with a demanding operating environment such as contamination, deformation and vibration of the surrounding structure.

In the meantime, the demand for safety is increased, asking for extended fatigue life and reliability. Modern bearings are also asked to be lighter and cheaper both for supply and maintenance.

These requirements induce bearing designed with thin sections, with integrated functions such as flanges, squirrel cages, or integrated bearing raceways.

The economic aspects require a process with the minimum amount of distortion and grinding and the maintenance costs require raceways more tolerant to surface damages.

To offset the deficiencies of through hardened and carburised steels with regard to surface resistance and toughness mainly, the nitriding of the 32CrMoV13 steel grade has been optimized.

2. Material requirements of aerospace bearings

The history of aircraft turbine engine bearings shows great improvements in reliability and performance due to the simultaneous progress in steels both in composition and quality to sustain the development of new engines 1). The through hardened M50 steel (80MoCrV42-16) developed during the late 50’s to fulfill the increase in operating temperature shows, as other through-hardened steels, limited high speed capabilities. Indeed, the high tensile hoop stresses resulting from ring centrifugal stresses at high rotational speed and press fit of the bearing ring, are liable to cause the following problems:

• added to the rolling contact stresses, they increase the overall stressing and may reduce the bearing fatigue life.
• over approximately 2.4 millions \( d_n \) (bearing bore in \( \text{mm} \times \text{shaft speed in min}^{-1} \)), they increase the stress intensity so that fatigue spalling which may arise can lead to fracture of rings 2).

High temperature case hardening steels such as

*SNR Elemental Bearing Technology
M50 NiL (13MoCrNi42-16-14) and X20WCr10 used later on, brought improvements, not only in relation with their tough core but also due to the achievement of compressive residual stresses in the case. The residual stresses influence the equivalent stress distribution and consequently the initiation and propagation of cracks, thus retarding the fatigue process.

Nevertheless, the fracture toughness of these steels remains poor. They are also subjected to the common disadvantage of carburizing steels regarding the important distortion induced by oil quenching during the heat treatment process that requires expensive grinding and impacts manufacturing costs.

Moreover, under high speed conditions, the lubrication is not permanently fully flooded (EHD) but may be mixed or starved (at least during the transient periods) so that surface fatigue is experienced. In these conditions, both through hardened steels and carburized steels show limitations.

3. The development of nitriding 32CrMoV13 steel

The operating conditions, design and manufacturing aspects of the aeronautical bearings previously described require a hard surface and a tough core, ie a surface hardened steel.

Surface modification processes such as nitriding have an advantage over carburising because they usually provide higher hardness, impart higher compressive residual stresses in the subsurface, both properties known to improve indentation damage and sliding wear resistance. The alloy elements (Cr, Mo, V, Mn and Al) added in nitriding steel to improve the solubility in ferrite conditions and to promote fine precipitation that strengthen the diffusion layer, are also favorable for fracture toughness.

Contrary to carburising, the nitriding treatment performed at relatively low temperature (500 - 550 °C), on pre-treated material, without subsequent quenching, leads to low distortions, while maintaining a structural and mechanical stability during temperature holding.

According to these features, nitriding of 32CrMoV13 grade, already used for other mechanical applications, offers a good solution to the complex and numerous problems of modern bearings, provided the depth of the case will be deep enough to be compatible with Hertzian stresses. This particular point implies the development of a deep nitriding treatment.

3.1 The base steel

The chemical composition of the 32CrMoV13 Steel grade, that has been standardized as AMS 6481 is given in Table 1.

Table 1 Chemical composition of 32CrMoV13 as per AMS6481

<table>
<thead>
<tr>
<th>Elements (%)</th>
<th>C</th>
<th>Cr</th>
<th>Mo</th>
<th>V</th>
<th>Mn</th>
<th>Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>32CrMoV13</td>
<td>0.29</td>
<td>2.80</td>
<td>3.30</td>
<td>1.20</td>
<td>0.15</td>
<td>0.70</td>
</tr>
<tr>
<td>AMS 6481</td>
<td>0.36</td>
<td>3.40</td>
<td>1.20</td>
<td>0.35</td>
<td>0.70</td>
<td>0.10</td>
</tr>
<tr>
<td>M50NiL</td>
<td>0.11</td>
<td>3.00</td>
<td>4.00</td>
<td>1.13</td>
<td>0.15</td>
<td>0.10</td>
</tr>
</tbody>
</table>

NOTE: Other than the components listed above, M50NiL contains 3.20 to 3.60% of Ni.

A VIM + VAR (Vacuum Induction Melting + Vacuum Arc Remelting) melting process is performed, in order to achieve a good level of micro-inclusion cleanliness required to obtain both high and reliable rolling contact fatigue properties and structural fatigue resistance.

The case hardness after a nitriding treatment depends on the hardness of the base metal (measured conventionally at the depth = Hv core hardness + 100 Hv), determined by the heat treatment, and on the composition of the steel, particularly the amount of elements promoting nitride precipitates (Cr, Mo, V, Al).

The 32CrMoV13 steel is a good compromise, in order to achieve surface hardness higher than that of carburized steels, with a rather good diffusivity of nitrogen for acceptable nitriding duration (deep case ≥ 0.6 mm in 100h max). It should be made without Al for a better nitried layer toughness, without Ni and with a close control of residual elements such as P (avoid temper embrittlement) for a higher core toughness.

3.2 Nitriding treatment

Prior heat treatment

Nitriding process is performed on parts, after prior heat treatment, in a more advanced stage of machining. Although distortion during nitriding is smaller than for carburized and quenched parts, it is necessary to induce a distortion as low as possible and to control it.

One major cause of part distortion during nitriding is the softening of the base metal, due to complementary tempering effects.

The effect of different nitriding treatments (from 25 h to 100 h at 555 °C) on the softening of the base metal for different initial hardness values (from 400 to 480 Hv) is shown in Fig. 1.

In order to restrict distortion after a treatment as long as 100 h, needed to obtain the required case depth, the initial hardness should be close to 380 -
420 HV, which corresponds to a tempering temperature in the range 625 - 650˚C.

The typical mechanical properties obtained after prior heat treatment compared to AMS 6481 requirements are given in Table 2.

A comparison between fracture toughness and rotative bending endurance limit of 32CrMoV13 and M50NiL carburizing steel is given Table 3. The better toughness of 32CrMoV13 can be explained by both a slightly lower strength, along with a composition and a microstructure less sensitive to temper embrittlement. The fatigue limit is comparable or higher than that of M50NiL. It may be due to the detrimental effect of the coarser grain size of M50NiL.

The deep nitriding process

The basic principle of the process, is to build up, right from the beginning of the cycle, on the outermost surface of the parts, a uniform white layer made of nitrides γ’ (Fe₂N) and ε (Fe₂₃N), by setting the nitriding potential of the atmosphere to a high value. A stable white layer, guarantees a permanent source of nitrogen to the diffusion layer, thus avoiding any nitriding defects (de-nitriding or heterogeneous nitriding) of the surface.

The nitriding depth is controlled by solid state diffusion and precipitation, mainly depending on the amount of nitrogen introduced in the subsurface and on the time-temperature cycle. The conventional depth of the diffusion layer, as a function of time and temperature, was measured on samples nitrided in an industrial equipment (Fig. 2).

In order to obtain a depth of more than 0.6 mm required by applications, in less than 100 h, nitriding should be performed in the range 525 - 550˚C. The temperature (class 5 vertical furnace) and the furnace atmosphere are controlled in order to maintain a stable thickness for the white layer that guarantee an homogeneous treatment.

Table 2 Mechanical properties of 32 CrMoV13 compared to the requirements of AMS 6481

<table>
<thead>
<tr>
<th></th>
<th>Hardness (Brinell)</th>
<th>U.T.S (MPa)</th>
<th>Yield Rp 0.2 (MPa)</th>
<th>A (%)</th>
<th>Z (%)</th>
<th>K_I Impact strength (J)</th>
<th>K_hC Toughness (MPa m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMS 6481</td>
<td>352 – 388</td>
<td>≥ 1137</td>
<td>&gt; 951</td>
<td>≥ 13</td>
<td>≥ 68</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Typical values</td>
<td>370 – 380</td>
<td>1250</td>
<td>1060</td>
<td>16.5</td>
<td>70</td>
<td>133</td>
<td>154</td>
</tr>
</tbody>
</table>

Table 3 Comparison of main mechanical properties of 32CrMoV13 and M50NiL carburizing steel

<table>
<thead>
<tr>
<th></th>
<th>UTS Rm (MPa)</th>
<th>Yield Rp0.2 (MPa)</th>
<th>A (%)</th>
<th>K_I-C 20˚C MPa m</th>
<th>Endurance Limit 10^7 cycles (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>32CrMoV13</td>
<td>951</td>
<td>1137</td>
<td>13</td>
<td>130</td>
<td>770</td>
</tr>
<tr>
<td>M50NiL</td>
<td>1060</td>
<td>1250</td>
<td>16.5</td>
<td>55</td>
<td>750</td>
</tr>
</tbody>
</table>

4. Properties of the deep nitrided layer

4.1 Microstructural characterization

Structure after prior heat treatment

Before nitriding, the steel is quenched and tempered at 625-650˚C corresponding to the 3rd stage of martensite tempering. The ferrite structure have retained the size of the early martensite laths that ranges between about 0.1 and 1 µm, while tempering carbides precipitate at the lath boundaries and inside the laths. The intragranular carbides are rodlike shaped, about 100 nm in length and arranged in two families oriented 65 degrees from each other (Fig 3). These carbides have been identified as cementite Fe₃C.
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Structure after nitriding
Nitrogen and carbon concentration profiles have been made through the diffusion layer using an electron microprobe (Fig. 5b). The amount of nitrogen introduced into the surface in the ferrite condition is above 1% Wt in the main part of the diffusion layer and decreases rapidly beyond 500µm in depth. In the meantime, the carbon content is well beneath the content of the base material, then increases to reach a maximum at about a depth of 600 - 700 µm that coincides with the maximum of the diffusion front of nitrogen. Some local carbon peaks reveal the presence of carbide precipitates.

It could be noticed that the hardness profile varies accordingly to the nitrogen profile.

The white layer (compound layer), less than 30 µm deep, combine porous Fe$_{2-3}$N-$\epsilon$ nitride on the outer side with compact Fe$_4$N-$\gamma' $ nitride on the inner side. Some branchings may grow along grain boundaries (Fig. 4). The white layer is systematically removed by grinding, on the rolling races and working surfaces (typically 70-80 mm).

The diffusion layer is divided in 2 zones (Fig. 5a):
- A zone, beneath the white layer, about 100 µm deep, relatively depleted in precipitates.
- A zone, toward the core, where "angel hair" precipitates are present, along the grain boundaries, in the direction parallel to the surface. These precipitates have been identified as cementite carbides.

The lack of carbide precipitation in the first zone could be explained by the dissolution of carbides and the precipitation of more stable nitrides. It results that the carbon is pushed inward by the nitrogen diffusion, leading to the precipitation of "angel hair" carbides.

After the nitriding process, the microstructure of the diffusion layer retains the tempered martensite morphology as observed after prior heat treatment. Inter and intragranular carbides are still observed, except in the sub-surface zone where most of them have disappeared being replaced by smaller nitride or carbonitride precipitates.

A fine nano-metric precipitation of disk-shaped nitrides also occurs inside the needles in the whole diffusion zone. Diffraction and high resolution T.E.M pictures (Fig. 6a and Fig. 6b) of these semi-coherent precipitates show they are of CrN type, only a few interatomic distances wide, while their diameter is about 10 nm.$^8$
Two other types of precipitates have been observed:

- Large (Fe,Cr)₃C carbides, probably residual carbides in which small globular precipitates are formed. These precipitates are chromium nitrides, partially substituted with vanadium and molybdenum.

- Intergranular precipitates, probably resulting from former intergranular carbides: A few isolated globular precipitates (about 100 nm in depth), identified as vanadium carbonitrides with partial substitution in chromium and molybdenum and other precipitates, smaller than 50 nm which are chromium nitrides partially substituted with vanadium and molybdenum.

The structure of the core does not evolve significantly after nitriding, only the mechanical properties slightly decrease (Table 4).

### 4.2 Mechanical properties

The nitriding process induces metallurgical transformations that result in changes of the macroscopic mechanical characteristics:

- **A significant hardening of the surface layer.**

  The surface hardness of the parts ranges between 730 and 830 HV30 with a case depth between 0.55 and 0.75 mm. This value is achieved after removal of the "white layer" (75 µm removed in average by grinding). A typical hardness profile is shown Fig. 7 in comparison with carburised M50NiL. The surface hardness of the nitrided 32CrMoV13 steel is higher than that of the carburized M50NiL steel, but the case depth is shallow.

  The hardness and other mechanical properties are maintained after 100h ageing at 450˚C for both nitrided case and core (Table 4). On the other hand, the hot hardness of the nitrided layer (surface hardness) is comparable to that of M50 steel (Fig. 5).

- **Compressive residual stresses.**

  The formation of nano-metric nitrides induce an expansion of the ferrite matrix which, according to the principle of the mechanical balance, builds up the observed stresses (Fig. 8). The residual stresses were measured using X-ray diffraction in the circumferential direction on a ball bearing race ground and polished. The high level of compressive stresses observed in the first 10 µm is due to the work hardening produced by the grinding process, while the rise between the depth of 100 µm and 200 µm is probably linked to the growth of precipitates in this zone.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Surface</th>
<th>Case</th>
<th>Core</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vickers hardness</td>
<td>Nitriding depth</td>
<td>Vickers hardness</td>
</tr>
<tr>
<td>As treated</td>
<td>HV10</td>
<td>375</td>
<td>375</td>
</tr>
<tr>
<td>Nitrided</td>
<td>HV50</td>
<td>615</td>
<td>0.60</td>
</tr>
<tr>
<td>After ageing</td>
<td>450°C/100H</td>
<td>822</td>
<td>0.70</td>
</tr>
<tr>
<td></td>
<td>550°C/100H</td>
<td>741</td>
<td>0.80</td>
</tr>
</tbody>
</table>

**Table 4** Modification of mechanical properties after ageing

**Fig. 6 a)** High resolution image of semi-coherent precipitates. 
**b)** Inverse Fourier Transform showing the very thin width (≈3-4 atomic planes)

**Fig. 7** Hardness profile of the nitrided layer

**Fig. 8** Residual stress profile
With a maximum peak value of about -550 Mpa, the compressive residual stresses are much higher than that of case hardened M50NiL (~ -200 Mpa), and of course higher than that of through hardened steels (no residual stresses except the grinding one).

### 4.3 Rolling contact fatigue properties

The ability to resist rolling bearing fatigue is a prime requirement for bearing steels, both concerning subsurface initiated fatigue and surface initiated fatigue. Subsurface fatigue, experienced under EHD lubrication conditions is linked to the micro-inclusion cleanliness but is not assumed to be the critical damaging process for remelted steels.

According to the Hertzian theory, rolling contact under EHD lubrication conditions is characterized by a sub-surface stress field whose maximum is located at a depth related to the contact loading. The case depth of nitrided parts (as well as for carburised one) has to be fitted to the Hertzian stress profile in such a way that the profile of micro-yield stress limit \( \tau_f(z) \) is above the equivalent stress curve \( \tau_d(z) \) related to the loading conditions.

In this way, a method for determining the profile of compressive micro-stress yield in the nitried case, based on nano-indentation measurements, has been developed\(^{10-11}\). The comparison of the evolution of the micro-limit profile with the loading stresses can then provide an evaluation of the potential risk of subsurface damage.

Fig. 9 shows the local equivalent stress profile representative of the loading conditions (Hertzian stress = 3100MPa) for NJ212 cylindrical roller bearings compared to the micro-yield shear stress limit of M50 and nitried steel (the local micro-yield stress is taken at \( 2 \times 10^6 \) plastic strain).

The middle curve represents the maximum shear stress for the M50 steel without any stress raiser (such as for example oxide inclusions, carbides...). The upper curve is the local maximum shear stress taking into account the local stress concentration due to carbides. The lower curve is representative of the nitried steel, including the compressive residual stresses that reduce the local value of the maximum shear stress.

Therefore, the M50 steel may develop fatigue subsurface cracks up to 600 \( \mu \)m in depth contrary to the nitried steel which is theoretically free from local structural modifications in the area of maximum Hertzian shear stress and thus not subjected to damage except for depth over 550 \( \mu \)m, where the stress is relatively low and the risk unlikely to happen.

Several types of rolling contact fatigue tests were performed, under various lubrication and operating conditions, in order to qualify the behavior of the nitried case.

### Fatigue life under EHD lubrication conditions

Rolling contact fatigue tests under fully flooded oil lubrication were performed for different type of contacts (testing conditions and results are given Table 5):
- flat washer (trust bearing) on the SNR FB2 test machine
- 6309 deep groove ball bearing on SNR standard "S" machine
- NJ212 roller bearing on SNR "FC" bench

For all these tests, the rolling elements were made from through hardened steel.

Both for point and linear contacts, the endurance tests show a fatigue life better for the deep nitried 32CrMoV13 steel than for trough hardened or carburized steels. On deep groove ball bearings and tapered roller bearings, the life is about 2 to 3 times the life of M50 steel.

![Fig. 9 Comparison of local maximum shear stress for NJ212 bearings (PHz=3100MPa)](image)

<table>
<thead>
<tr>
<th>Test conditions</th>
<th>Bearing type</th>
<th>Flat washer</th>
<th>6309</th>
<th>NJ212</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial load (daN)</td>
<td></td>
<td>1075</td>
<td>530</td>
<td>300</td>
</tr>
<tr>
<td>Radial load (daN)</td>
<td></td>
<td>—</td>
<td>1600</td>
<td>1200</td>
</tr>
<tr>
<td>Hertzian stress (MPa)</td>
<td></td>
<td>4200</td>
<td>3200</td>
<td>3100</td>
</tr>
<tr>
<td>Speed (min(^{-1}))</td>
<td></td>
<td>1500</td>
<td>2200</td>
<td>1200</td>
</tr>
<tr>
<td>Lubrication</td>
<td>ISO 46 oil</td>
<td>ISO 46 oil</td>
<td>ISO 46 oil</td>
<td></td>
</tr>
<tr>
<td>Temperature (˚C)</td>
<td>40</td>
<td>Room Temp.</td>
<td>Room Temp.</td>
<td></td>
</tr>
<tr>
<td>M50</td>
<td>≥ 1300</td>
<td>3863</td>
<td>1240</td>
<td></td>
</tr>
<tr>
<td>M50 Nil</td>
<td>≥ 1300</td>
<td>942</td>
<td>560</td>
<td></td>
</tr>
<tr>
<td>X20WCr10</td>
<td>850</td>
<td>—</td>
<td>980</td>
<td></td>
</tr>
<tr>
<td>Life (h)</td>
<td>990</td>
<td>—</td>
<td>—</td>
<td></td>
</tr>
</tbody>
</table>
Fatigue life under boundary lubrication

Tests have been made on FB2 machine using NATO 0156 oil at room temperature under a 2500 MPa contact stress. In these conditions, the lubricant oil film parameter $\lambda = \text{oil film thickness}/(\text{Ra}_{\text{raceway}} + \text{Ra}_{\text{ball}})^{1/2} \approx 1.5$. Comparative results for M50NiL, M50 and 32CrMoV 13 are given in Table 6.

Considering the experimental results, the behavior of the deep nitrided 32CrMoV13 steel that experienced no failures is much better than carburised M50NiL that shows peeling damage.

Table 6: Rolling contact fatigue under boundary lubrication and of dented raceways (flat washer)

<table>
<thead>
<tr>
<th>Condition</th>
<th>$L_{10}$ (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boundary lubrication</td>
<td>218</td>
</tr>
<tr>
<td>Dented raceways</td>
<td>123</td>
</tr>
<tr>
<td>M50NiL</td>
<td>&gt;900</td>
</tr>
<tr>
<td>M50</td>
<td>&gt;900</td>
</tr>
<tr>
<td>32CrMoV13 DN</td>
<td>&gt;900</td>
</tr>
</tbody>
</table>

Simulation of contaminated lubrication

Under contaminated lubrication conditions, the life of bearings decreases and surface initiated spalling occurs on dents produced by foreign particles going through the contact. The effect of the shape and size of artificial dents on the bearing life provides useful information with regard to the fatigue life under contaminated lubrication.

For this purpose, tests have been performed on the SNR FB2 machine. Four Vickers dents, 280 mm in diagonal, had been printed on the race before testing. Rings were run under a 2500 MPa Hertzian stress using NATO 0156 oil lubrication.

Deep nitrided 32CrMoV13 steel shows a longer life compared to M50 and M50NiL steels (Table 6). Tests were interrupted after 900 hours without any failure having been observed, contrary to M50 and particularly M50NiL that experience early failure.

This favorable behavior could be explain by the combined effects of large surface hardness and high compressive residual stresses.

5. Industrial statistics and products

When the nitriding conditions described previously are applied, after proper prior heat treatment for hardness 380 - 420 Hv, the statistical results for hardness, conventional depth and distortion measured on more than 70 batches of a 150 mm outer ring, are given in the Table 7. These results confirm the great reproducibility of the process.

Bearings with different shapes and sizes are manufactured by SNR Roulements using deep nitrided 32CrMoV13. It concerns deep groove ball bearing, roller bearing with thin sections and/or complex integrated shapes such as bearing for main shaft of aircraft turbine engines or rotor mast of helicopters (Fig. 10).

Table 7: Metallurgical and dimensional properties of deep nitrided parts

<table>
<thead>
<tr>
<th>Specification</th>
<th>Average value</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>As nitrided depth (mm)</td>
<td>0.63~0.75</td>
<td>0.67</td>
</tr>
<tr>
<td>Depth on finish parts (mm)</td>
<td>≥0.55</td>
<td>0.60</td>
</tr>
<tr>
<td>White layer (μm)</td>
<td>≤35</td>
<td>25</td>
</tr>
<tr>
<td>Surface Hardness (HV0.5)</td>
<td>750~850</td>
<td>795</td>
</tr>
<tr>
<td>Core surface (HV0.5)</td>
<td>360~420</td>
<td>400</td>
</tr>
<tr>
<td>Diameter expansion ratio</td>
<td>--</td>
<td>0.8</td>
</tr>
<tr>
<td>Out of roundness (μm)</td>
<td>--</td>
<td>25</td>
</tr>
</tbody>
</table>

Fig. 10: Example of aerospace bearings
6. Conclusion

The deep nitriding process applied to 32CrMoV13 steel (AMS 6481) solves in a convenient way the difficult compromise concerning the incompatible properties required for aerospace bearings.

Indeed, these bearings may operate under severe conditions such as high-speed, high temperature, starved or contaminated lubrication. Furthermore, their design may be complex, integrating multiple functions, and requires thin sections for weight reduction.

The Deep Nitriding of 32CrMV13 steel offers a better compromise than classical high temperature bearing steels (through hardened or carburized) to meet these requirements.

The core material has excellent toughness for structural functions and high rotational speeds. Due to the semi-coherent precipitation of nano-metric nitrides, the nitrided layer features high hardness, high compressive residual stresses and superior rolling contact properties.

The nitriding technology makes easier the production of parts with complex shapes, with a limited amount of finish grinding because of the limited distortions resulting from low temperature cycle. The manufacturing process is under control and properties show small dispersion.

All these features make the deep nitrided 32CrMoV13 an excellent solution for high reliability and safety aerospace components.

Acknowledgment: Author would like to thank the Aubert & Duval Company and the Mateis laboratory of Lyon INSA for their collaboration to this work.

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