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GAS NITRIDED STAINLESS STEEL WITH REDUCED HARDNESS GRADIENT TO HIGH LOADED AND CORROSIVE ENVIRONMENT[1]

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Abstract

The nitrided stainless steel is applied on engine components in order to reduce the wear under operation. One application of this is on piston rings. Using the gas nitriding process it is the main application on the top compression rings in Europe and Mercosul. This application is the one with worst tribological conditions once it is near to the combustion chamber exposed to the highest mechanical and thermal loads. When the engine is designed to run with Ethanol in a flex fuel design, the mechanical load increases between 20 to 30% and the sub-products of combustion presents higher corrosion characteristics then when it is run with gasoline. It is also observed a mechanism of detachement called spalling in the mentioned running conditions. Under this agressive environment it was designed a new stainless nitriding treatment in order to improve the toughness through specific hardness gradient. Such development not only reorganized the hardness gradient but also redistributed the carbides in a different arrangement than current process. This arrangement eliminated the occurrances of "angel hair" which also improved the toughness of the nitrided layer. Rig tests and engine tests were conduced in order to evaluate fatigue, scuffing and wear resistance of the developed treatment when applied in a top compression ring of flex fuel engines running with Ethanol.

Keywords: Gas nitriding; Environmental cracks; Ethanol.

AÇO INOXIDÁVEL NITRETADO COM GRADIENTE DE DUREZA REDUZIDO PARA AMBIENTES DE ALTO CARREGAMENTO E CORROSIVIDADE

Resumo

O aço inoxidável nitretado é aplicado em componentes de motor com o intuito de reduzir o desgaste em operação. Um exemplo dessa aplicação são os anéis de pistão. Usando o processo de nitretação a gás, essa é a principal aplicação em anéis de compressção na Europa e no Mercosul. Essas aplicações são as de piores condições tribológicas, uma vez que está próxima à câmara de combustão, exposta às maiores cargas mecânicas e térmicas. Quando o motor é prejetado para operar com Etanol em um conceito de abastecimento flexível, as cargas mecânicas aumentam de 20 a 30% e os sub-produtos da combustão apresentam maior características de corrosão do que quando se roda com gasolina. Também é observado o mecanismo de destacamento chamado *spalling* nas condições de teste mencionadas. Nesse ambiente agressivo, foi projetado um novo tratamento de nitretação com o intuito de melhorar a tenacidade através de um gradiente de dureza específico. Tal desenvolvimento não só reorganizou o gradiente de dureza mas também redistribuiu os carbetos num arranjo diferente do que o do processo corrente. Esse arranjo eliminou as ocorrências de "cabelos de anjo" que também melhoraram a tenacidade da camada nitretada. Testes de bancada e testes de motor foram conduzidos com o objetivo de avaliar resistência a fadiga, travamento e desgaste do novo tratamento desenvolvido quando aplicado em um anel de de pistão de compressão para motores de abastecimento flexível funcionando com Etanol.

Palavras-chave: Nitretação a gás; Trincas por meio ambiente; Etanol.

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INTRODUCTION

Nitriding is a termochemical surface treatment normally applied to steel components in order to provide better wear resistance, higher hardness and also to improve high cycle fatigue resistance.[1,2]

Among the different techniques to increase surface nitrogen contend in steel components, the gas nitriding has been applied in the piston ring industry,[3] and can be classified as one of the best process to run nitriding in such thin component in order to enable protection at all external surface. It is used ammonia gas as a source of Nitrogen. When ammonia gets in contact with the steel, it is dissociated releasing atomic nitrogen, which is further absorbed by the steel and interstitially dissolved on iron (Fe). When the surface reaches a certain saturation level it is promoted the formation of nitrides through nucleation and growth mechanisms.

As previously mentioned, nitriding treatment increases hardness and wear resistance through a surface thermo-chemical treatment. The process temperature, around 500 to 570°C, allows the Nitrogen to be introduced in steel without ferrous phase transformation, than Nitrogen diffusion occurs in the ferritic phase. The nitrogenous activity environment control, associated to a certain temperature, promotes the ideal increase in hardness to guaranty wear resistance associated with other characteristics. As well, it is improved mechanical properties and high environmentally crack resistance of the steel.[1,2]

This surface treatment allows material transformation up to a certain depth from the surface, keeping the nucleus material ductile and tough, with little volume and shape change due to the lack of phase transformation when the steel is cooled to room temperature. As well known in the skilled of the art, in nitriding processes the surface region of the material is the one wich receives the most nitrogen absorption, as the depth from the surface increases, the abosrved nitrogen decreases. Analogous, the material hardness is higher at the surface, decreasing with the increase of depth from the surface.

Among the advantages of nitriding it is important to highlight:

- High surface hardness with increased wear resistance;
- High fatigue resistance – compressive residual stresses in the nitrided layer of the steel;
- Elevated dimensional stability.

Progress in engine technology has been accelerated dramatically in the last years mainly due to power environment requirements. Emission restriction legislation defined for the near future shall reduce in nearly ten times standards of engines in production line today.

Engine technology trends indicate cylinder pressure increase, higher operating temperatures, and more abrasive environments by the recirculation of exhaust gases to the combustion chamber. It is also required lower cylinder liner surface roughness thus leading to lower lube oil consumption and lower blow-by levels. Also, continuous increase production of Flex-fuel engines has lead to combustion calibrations more aggressive than with gasoline use.[4,5] Such demands, associated with increase in specific power requirements lead to thermo-mechanical loadings, aggressive environmental conditions, which challenge the tribological behavior of piston rings. The piston rings will have to withstand such demanding conditions, with low wear and high durability to comply with the requirements along the whole engine life.

Based on engine technology trends, nitrided steel has been used to improve tribological properties of the piston rings. Besides the demand for excellent wear and scuffing resistance, due to the extreme operating conditions, the nitrided steel ring also needs excellent resistance to cracking and spalling.[6]

The object of the paper is to present a nitrided steel piston ring with superior sliding characteristics which does not cause disturbance for the good operation of the engine. Such disturbances are commonly related to damage caused by spallation of the ring material or extreme high wear.

INNOVATIVE NITRIDING TREATMENT

To counter demanding engine environment conditions it was developed a novel nitriding case with improved toughness. A nitrided product was developed, with increased toughness ductility, aiming reduction of crack formation and propagation. In order to enhance crack nucleation and propagation resistance.

The resultant product has a surface hardness of a close to 650HV0.1, much smaller than typical product for this application and a total nitriding layer thickness of about 60 μm.[7] A very fine network of complex carbo-nitrides was observed. A typical nitrided ring for this application has a surface hardness of about 1100HV0.1.[1,2]

It is believed that the hardness provided by the nitrided layer is directly linked with wear resistance. Nitriding process temperature for all steels is between 495 and 565 ^{o}C.[1,8]

The rings were nitrided according to a novel recipe. An unique combination of nitriding parameters produced a case where although the surface hardness was maximum 800HV0.1, well below 1200HV0.1 as the typical GNS, even tough the wear resistance was not affected. The lower hardness and a different microstructure resulted in a case with higher spalling resistance, as described ahead.

The new product was aimed at reduction of crack nucleation formation and propagation, maintaining the good characteristics on wear resistance.

The novel nitriding case presents a different nitriding network pattern than the current GNS, the latter shows precipitation of fine carbides at grain boundaries, parallel to the surface, typical of such treatment. See Figure 1. These carbides, although fine, under high cyclic working loads, can create conditions to crack propagation through the grain boundaries (where the carbides are precipitated), a potential source for cracking mechanism possibly originating cracks with consequent GNS surface detachment (spalling).

Figure 1. Typical GNS layer showing fine carbides precipitated at grain boundaries.

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In opposition to that, the new nitriding layer are free from carbide precipitation. See Figure 2. Once there is no carbide precipitation, the material is more resistant to crack generation. That, together with the reduced hardness, which makes it difficult for the cracks to propagate, it is created a ring with high resistance to crack nucleation formation and propagation, meaning a ring with high resistance to spalling occurrence.

Figure 2. No occurrence of carbide precipitation in innovative nitriding.

The comparison of Figures 1 and 2 present the elimination of "angel hair" for the new treatment which also contributed to the improvement of the layer toughness.[9]

RIG TEST RESULTS

Surface toughness can be investigated by scratch test. A diamond stylus is used to scratch the surface. The load to produce surface cracks and the crack appearance are indicatives of the surface toughness. Occurrence of the so called Chevron cracks (Forward Chevron Tensile cracks) is associated with lower surface toughness. Figure 3 shows the typical appearance after scratch test on the baseline GNS, with Chevron cracks. Figure 4 shows the GNS-Flex after the same test, with only “Arch” cracks, sign of higher toughness.[9]

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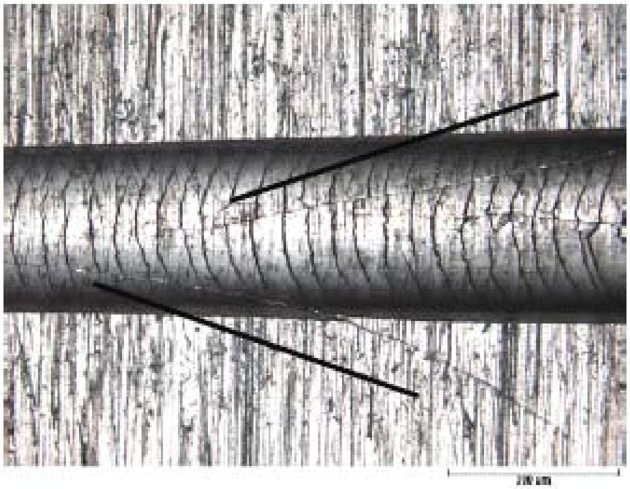

Figure 3. Chevron cracks on the baseline GNS under scratch test.

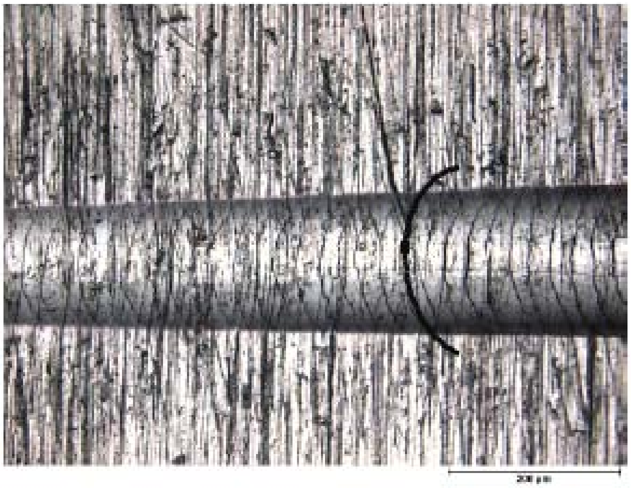

Figure 4. Only "Arch" cracks on the innovative GNS after scratch test.

Tribology tests were performed in order to assess the scuffing resistance of the new GNS. The test was conduced in a "Block on Ring" bench device. The test consists on increasing the normal load by 50N up to 500N. It the test is run at 900 rpm and it is monitored the friction coefficient. When it is reached 0.3 in the friction coefficient, it is considered scuffing. The test is replicated on 15 parts and the index is given by the average of scuffing load divided by 500N. The new product (GNS-Flex) showed similar scuffing resistance compared to the regular GNS, see Figure 5.

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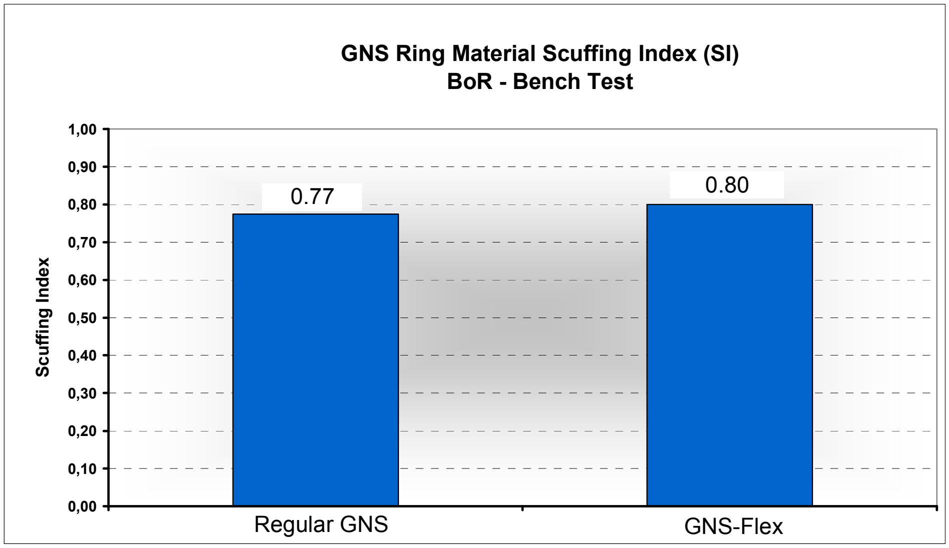

Figure 5. Comparative scuffing resistance ability of GNS-Flex (result from BoR bench test).

Fatigue resistance behavior was another characteristic assessed for the new product. It was performed a test dedicated to evaluate the fatigue resistance of piston rings. In this test the rings are submitted to alternative displacements, such as leading from a minimum stress of 400MPa (tractive at ring outer diameter) to a maximum tractive stress defined by test setup. The fatigue stress limit is defined by the highest tractive stress that the rings can support performing 2mio cycles (39Hz). A given stress is applied on 6 rings at the same time. If at least one ring is broken it is considered failure. It all 6 resists, it is performed another test for replication. Only if no ring fails in the two tests is when the maximum load is considered as resisted by the product. The results show similar behavior for regular GNS and GNS-Flex (see Figure 6).

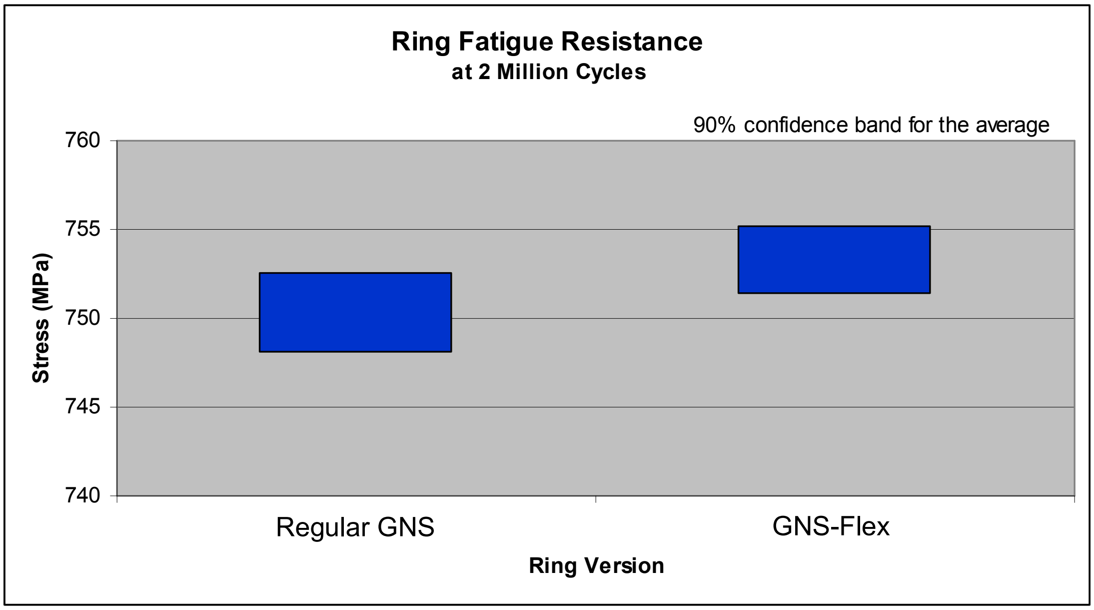

Figure 6. Fatigue resistance results for regular GNS and innovative GNS.

ENGINE TESTS - PISTON RING APPLICATION

Spalling resistance of the novel GNS was investigated trough a specific cyclic dyno engine test in a 1.6L flex fuel engine. When running with pure ethanol, E100, such engine test usually presents spalling on the top ring for an abusive dyno cycle. In several such tests, no occurrence of spalling was verified on the novel GNS case, while the current GNS presented several occurrences.[6] Figure 7 shows a typical result after 150h of such engine test. From these results it is possible to conclude that the new treatment presented increased resistance under high loaded and corrosive environment.

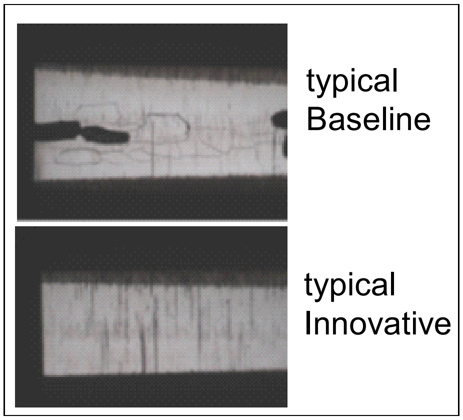

Figure 7. Top ring running face aspect after 150h engine test. 1.6L flex fuel engine (E100 fueled).

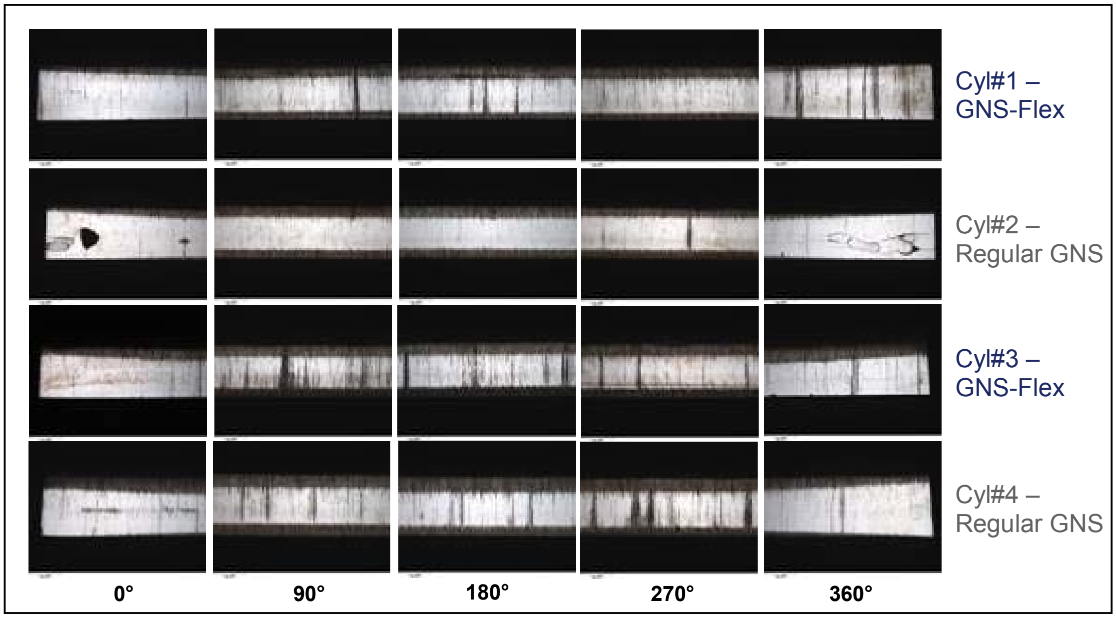

Figure 8. Top rings (running face) from 300h engine test. 1.6L flex fuel engine (E100 fueled).

Running face wear was similar for both regular and the new nitride recipe rings. Figure 9 presents the range of wear from the tested rings after 150h in an abusive engine test.

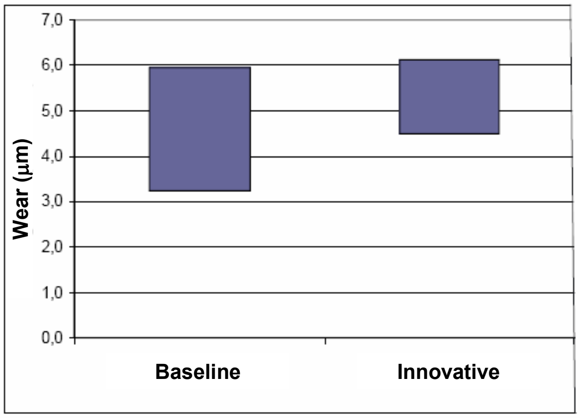

Figure 9. Running face wear of baseline and innovative nitriding after 150h engine test.

CONCLUSIONS

The development of the new nitriding treatment showed improved performance compared to conventional treatment from metallurgical and mechanical analysis. From metallurgical perspective the hardness gradient was achieved and the absence of "angel hair" was observed. These characteristics are recognized in the literature as important to improve toughness.[1,2,8] On the mechanical evaluation rig tests were conduced with improved results for the new treatment, among these tests: scratch tests in an identation rig, scuffing tests in block-on-ring rig and fatigue evaluation in piston ring device.

The new nitriding treatment named in here as GNS-Flex was also engine tested for a flex fuel engine running with Ethanol, which is considered more critical in terms of mechanical load and corrosive environment. In such tests the new treatment showed to be able to avoid occurrances of spalling which is a characteristic observed on tests of the conventional nitriding treatment. Due to the reduction of the hardness there was a concern of wear resistance which was not observed in the engine test.

Future work can try to explore the application of the new nitriding treatment on other products that should resist on such critical tribology environment.

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