MEETING NEW EURO VII BRAKE WEAR PARTICLE EMISSION STANDARDS

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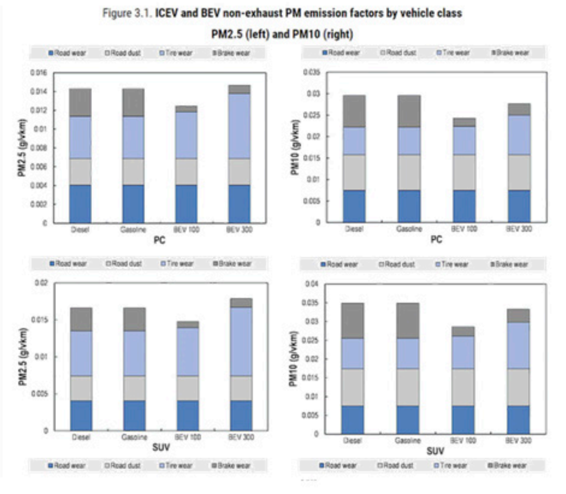
Brake emissions are a substantial source of particles in urban areas, increasing the total number of particles in the air and contributing to PM 2.5 pollution. In 2025, the European Commission is planning to present the new exhaust emission standard Euro 7 introducing stringent regulations on particulate emissions for passenger cars and commercial vehicles. As engine particulate emissions have been decreasing over the last decades, the major source for particulate matter (PM) and particulate number (PN) are now tires and braking systems. Applying ferritic nitrocarburizing process (FNC) on standard cast brake rotors is known to provide a technically and economically suitable solution when paired with a stress relieve (SR) process prior to final machining, considering a projected worldwide automotive disc brake market volume of USD 18 billion by 2025.

Nitrex R&D has long been investigating wear-resistant nitrocarburized, as well as nitrocarburized and post-oxidized surfaces on cast iron and steel parts and is providing a solution allowing for high-volume production of FNC brake rotors able to meet the requirements of automation companies and of companies from other fields of transportation.

In July 2022, the European Commission plans to present a concrete proposal for the future Euro 7/Euro VII emission standard for passenger cars and commercial vehicles such as trucks and buses, which is expected to come into force in 2025 [1].

The new regulations will force vehicle manufacturers to further reduce particulate emissions from cars, among other things. As powertrains have become cleaner and particulate matter from combustion has decreased over the last decades, the share of non-exhaust particulate emissions is getting into focus as their numbers are increasing in relative terms but also in absolute terms with the growing demand for transportation. Non-exhaust particulate emissions are mainly caused by abrasion from tires and brakes which applies as well to other transportation systems like rail and aviation.

As part of the Green Deal [2], the EU is now extending the fight against particulate matter to tires and brakes. Specifically for the latter, some solutions have already been developed to production maturity. However, they will only become more widespread when the EU's binding regulations require their use.



Source: OECD

FIGURE 1: Non-exhaust PM emissions by vehicle class

The **European Green Deal**, approved [in] 2020, is a set of policy initiatives by the European Commission with the overarching aim of making the European Union (EU) climate neutral in 2050. An impact-assessed plan will also be presented to increase the EU's greenhouse gas emission reductions target for 2030 to at least 50% and towards 55% compared with 1990 levels.

Source: Wikipedia [2]

FRICTION BRAKES – A TRIBOLOGY SYSTEM

From τρίβω (tribo), Greek for rubbing.

According to *Friction Brakes—About Tribology* [3] taken from tribonet.orgg and published on May 10, 2021, the primary purpose of a brake system is to slow down an object in motion and/or bring it to a standstill, using mainly so-called friction brakes. This system fulfills its function by pressing a brake lining (pads) against the moving part (rotor). This creates a frictional force that is opposite to the direction of the moving part. The kinetic energy of the moving object is thereby converted into heat.

Therefore, it is essential for the friction force to remain high and stable during the entire braking action, which applies to any condition involving a wide range of contact temperatures, contact pressures and relative velocities between the static and moving parts of the brake, including any environmental changes.

The braking action leads to wear and induces vibration that also contributes to noise. Consequently, the lifespan of a braking system is mainly determined by the wear of brake components, making the topic relevant from an environmental perception, especially as the worn particles released can negatively affect living organisms.

The design of brakes is determined by the physical properties of the components as they are responsible for the friction generation, the heat dissipation, and ultimately an effective stop due to friction; their wear resistance determines the lifespan of the brakes. In short, brakes should show optimum behavior in the aspects of efficiency, durability, space for installation, and cost.

Up to now, the primary target focused on minimizing friction-induced vibrations and associated noise and considerable enhancement has been achieved by modifying the contact surface's roughness and chemistry. With the new regulation, other parameters need to be considered: environmental friendliness paired with high stability and minimal need for maintenance.

Tribology is the science and engineering of interacting surfaces in relative motion. It includes the study and application of the principles of friction, lubrication, and wear.

Source: Wikipedia [4]

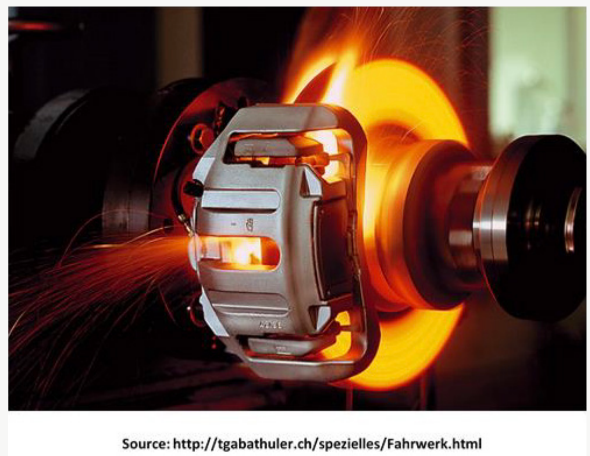


FIGURE 2: Red-hot brake rotor on a test stand

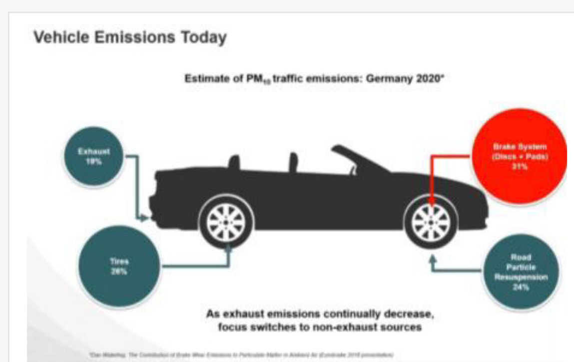


FIGURE 3: Estimated PM10 traffic emissions in Germany [5]

REDUCING BRAKE WEAR PARTICLE FORMATION

Taken from: https://www.bmb-consult.com [6]

"In September 2015 the LOWBRASYS research project co-financed by the European Horizon 2020 program and coordinated by Brembo was started setting the overall goal to reduce brake wear emissions by 50%.

''LOWBRASYS investigated into a variety of possible solutions, among them ceramic coating for the surface of brake discs and pads, bearing the capability to reduce the number of particles emitted by about 60-90% depending on the selected layouts, also limiting the total mass of emitted particulate by between 10-30%. Applying this technology to series production on the other hand will require further development steps, as the project's goals were of pre-competitive technical research.

''Changing the braking strategy by software on board a vehicle will allow for a 40% reduction in the number of emitted particles and a 20% reduction in the overall particulate mass.

"Adding a capture system to the brakes can reduce the number of emitted particles in a range between 15 -50% and reduce the emissions' mass by 10–30%. This system will be fitted near the caliper and directs the flow of particles towards a filtering point. Initial results of the capture device look promising and development for robust operation are still carried out.'' (sic)

The findings suggest that besides other measures like recuperation in EVs, specific software additions and cleaning/filter systems, reducing brake wear particle formation addresses replacement or modification of the brake system, consisting of multicomponent composite pads bound in a polymer matrix, and cast iron or steel rotors.

→ One very expensive solution would be **using carbon-ceramics**, typically found in high-end luxury and sports cars, and simply avoiding today's standard cast iron or steel discs. The production process requires pressing green bodies, converting them into ceramic components by carbonizing at 900 °C (1,652 °F), followed by siliconizing at 1,700,°C (3,092 °F). As such parts have very high hardness, final machining requires the use of diamond tools.

→ A more moderate modification would be **applying** a still very costly **coating process to standard brake discs** aiming for higher thermal conductivity to avoid high disc temperatures and therefore reducing wear and particle formation that increases proportionally at temperatures above 170 °C (338 °F). This coating technology would also harden the surface of the brake disc, further reducing wear and particle formation.

→ The most cost-effective alternative addressing mass production has been identified by **applying the ferritic nitrocarburizing process** (FNC) to finished standard cast iron brake rotors.

APPLYING THE FNC PROCESS TO REDUCE BRAKE-ROTOR CORROSION

General Motors (GM) began investigating solutions for brake-rotor corrosion and extended service life already in 2006, starting with salt bath nitriding, then implementing an environmentally friendly gaseous nitrocarburizing process [7]. By applying FNC, GM was able to reduce brake-related warranty claims by over 70% [8].

In 2011, GM brake engineer and materials expert Jim Webster presented the advantages of FNC brake rotors at the SAE World Congress & Exhibition [9].

"Ferritic nitrocarburized (FNC) cast iron brake rotors are proposed as a means to improve corrosion resistance, improve brake lining wear, as well as reduce corrosion-induced pulsation of automotive brake rotors. FNC processing of finish machined brake rotors presents challenges with controlling distortion, i.e., lateral run-out (LRO). Prior investigations of FNC brake rotors suggested grinding the rotors to correct distortion. Post-grinding the FNC-processed rotors may reduce the FNC layer with an accompanying reduction in performance. Stress relieving (SR) the casting prior to FNC was found beneficial in providing a dimensionally acceptable rotor."

General Motors has been applying this technology to minimize corrosion from its brake rotors, while at the same time doubling rotor service life. By 2016, the automaker was already using corrosion-resistant FNC rotors on 80% of its U.S. market vehicles.

GM's proposal addressing corrosion exposes rotors to a temperature of 560 °C (1,040 °F) for up to 24 hours within a nitrogen and carbon bearing atmosphere aiming for a 10-μm-thick compound layer across the entire rotor surface [7].

The resulting friction surface is significantly more durable than that of a rotor without the FNC treatment, while remaining virtually impervious to corrosion and rust, which doubles the rotor life. Other benefits include reduced brake dust accumulation on the road wheels and smoother brake-pedal feel over time.

PROCESS AIMED AT CREATING THE MECHANICAL PROPERTIES OF A FNC SURFACE LAYER

Taken from *ASM Handbook, Volume 4A*, edited by J. Dossett and G.E. Totten [10]:

"Ferritic nitrocarburizing is a thermochemical case-hardening processes whereby nitrogen and carbon are introduced into the surface of a solid ferrous alloy, in the ferritic state of the material. The nitrided layer created during treatment typically consists of a surface layer of iron nitrides and iron carbonitrides—referred to as a compound layer (also known as a white layer, due to its appearance in an etched micrograph). Underneath the white layer is a diffusion zone, which also contains carbonitrides of alloying elements. The principal reasons for nitriding and nitrocarburizing are:

"To improve wear resistance by providing

- *High hardness (compound layer, diffusion zone)*
- *Improved pitting resistance (diffusion zone)*
- *Chemical resistivity (compound layer)*
- *Low coefficient of friction (compound layer)*

"To improve strength behavior by providing

- *Improved fatigue life (diffusion zone, expanded austenite)*

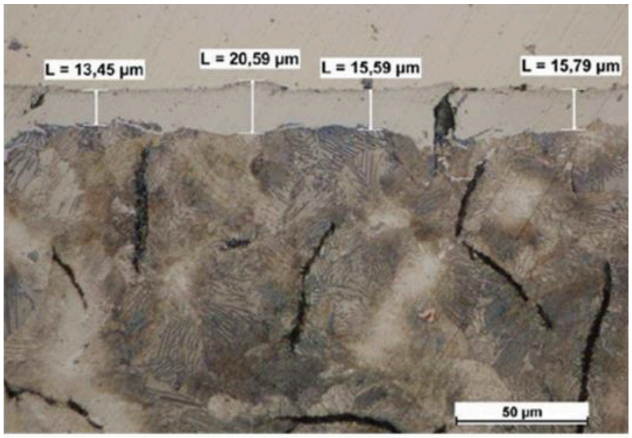
"To improve resistivity against the following forms of corrosion:

- *Neutral salt solutions (compound layer)*
- *Atmospheric corrosion (compound layer)*
- *Chloride ions—pitting (compound layer)*
- *Liquid metal (compound layer)*
- *Pitting (crevice) corrosion (expanded austenite)*

"To improve heat resistivity up to nitriding/nitrocarburizing temperature (diffusion zone)."

APPLYING FNC TECHNOLOGY TO MINIMIZE PARTICULATE EMISSIONS

Introduced in the early 2000s, FNC brake rotors are a proven technology that is now implemented by most of the leading automotive OEM and suppliers. Specifications of the FNC treated rotors may vary between manufacturers, leaving space for further optimization of properties of the nitrided phase. Using this cost-effective solution on mass production parts requires the use of heat-treating equipment and procedures matching stress relieve prior to final machining with the nitrocarburizing process thereafter to achieve optimum performance. The nitrocarburizing equipment and process must offer repeatability, reliably meeting customer requirements in terms of compound layer thickness, chemical composition, preferred nitride phase, and porosity.



Source: Nitrex, typical surface layer of an FNC process applied to cast brake rotors

FIGURE 4: Typical surface layer on grey cast after FNC

INCREASED ROTOR CORROSION—A CONSEQUENCE OF APPLYING ENGINE BRAKING AND ENERGY RECOVERY BRAKE SYSTEMS

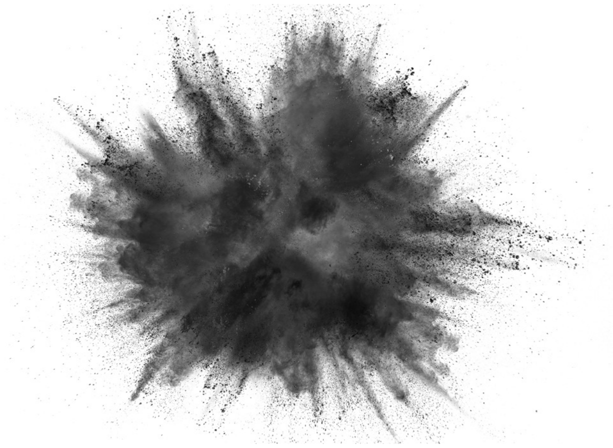
With the introduction of energy recovery systems and the use of engine braking by intelligent automatic transmissions, there is now increased corrosion of brake discs. Common brake discs are made of cast iron, and that simply rusts. If the brake is not in use, the rust coating is no longer abraded by the brake pads and the corrosion attack goes deeper, resulting in significantly higher brake disc wear, especially on the rear brakes [11].

Considering the new requirements of electromobility where mechanical braking is reduced to a minimum, corrosion attacks will increase. This results not only in visual defects but also in reduced performance of the entire brake system and a shorter service life [12].

Thus, owners of vehicles increasingly observe that during periodical inspections the brakes are objected to and must be replaced. An expensive solution to the problem is to equip the vehicles with ceramic or all-metal brakes made of coated aluminum or stainless steel, pushing up the price of the vehicle considerably.

Grey cast iron rotor corrosion affects not only the lifetime but also particle emissions. Corroded rotors cause a significant increase in particulate numbers and mass by 50% or more [13].

Consequently, brake rotors require not only a hard and thermally stable surface, but this surface should also have superior resistance to corrosion especially caused by salt water during wintertime.



HAZARDS CAUSED BY PARTICULATE EMISSIONS

Having a closer look on the impact of particulate emissions on health conditions reveals that this is not only a matter of mass (debris) but also size and chemical composition. While mass is mainly affecting the lifetime of the brake friction partners (pads and rotor), particulate size is responsible for picking up particles in the lung. Brake emissions should obviously not contain any toxic materials or heavy metals. Consequently, new braking systems will have to address all of them.

The influencing parameters for brake emissions are numerous and include rotor and pad material, hardness, roughness, friction, resistivity to temperature increase when applying brake pressure, thermal conductivity and heat capacity, chemical reactions between rotor and pad material at elevated temperatures creating toxic specimens, chemical reactions between rotor and pad material in wet conditions, roughness or porosity acting as a reservoir for particles while braking...

All of this will require extensive research in the future, also in the context of new technologies such as electrical drive trains, electro-mechanical brake systems and ultimately autonomous driving.

Nitrex's unique NITREG®-C is a nitrocarburizing process based on the proven NITREG® potential-controlled gas nitriding technology. It incorporates the simultaneous diffusion of carbon and nitrogen into the steel surface.

NITREG®-C is often specified in industrial applications on the merit of it being an environmentally friendly but equivalent alternative to salt bath nitrocarburizing. The purpose of the treatment is to create a hardened superficial layer, enhancing wear and corrosion resistance, or improving fatigue resistance of treated steel or cast iron parts, without distortion of shape or dimensional changes.

When resistance to corrosion and an attractive black finish are required, in-situ post-nitrocarburizing oxidation ONC® is the best technology.

In general, **wear** is mechanically induced surface damage that results in the progressive removal of material due to relative motion between that surface and a contacting substance or substances.

Source: material-properties.org [14]

... **fatigue** is the initiation and propagation of cracks in a material due to cyclic loading.

Source: Wikipedia [15]

Corrosion is a process in which a material is oxidized by substances in the environment that cause the material to lose electrons. Corrosion resistance is the capacity to hold the binding energy of a metal and withstand the deterioration and chemical breakdown that would otherwise occur when the material is exposed to such an environment.

Source: www.corrosionpedia.com [16]

ONC® is a clean technology producing a magnetite iron oxide layer that, in many instances, can replace chrome plating and salt bath nitriding with their inherent problems of pollution and cost. Depending on the type of steel, parts treated with the NITREG®-C + ONC® processes can easily pass well over 200 hours of salt spray test per ASTM B117 before the first corrosion spot appears.

Having been active in heat treating for decades and originally specializing in nitriding and nitrocarburizing, Nitrex does have a huge amount of experience in both fields, building the equipment but also operating it in the company's commercial heat-treating facilities around the world. Based on this experience and constant research focusing on mechanical and corrosion properties, the findings of a research project that started in 2017 will be presented in the following text.

Figure 5 gives an estimate on how the compound layer will grow over time at 560 °C (1,040 °F) with varying nitriding potentials. It can clearly be observed that nitrocarburizing of cast iron demands a high nitriding potential throughout the treatment to produce the required compound layer thickness (CLT) for brake rotors.

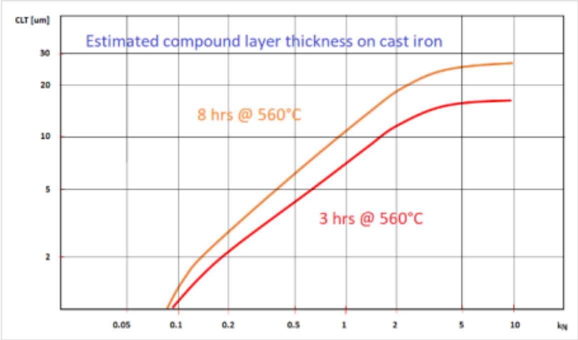


FIGURE 5: CLT growth rate on cast iron treated at 1,040 °F

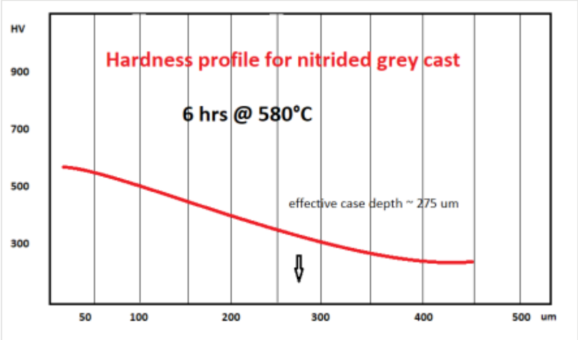


FIGURE 6: Hardness profile on a FNC grey cast iron treated at 1,076 °F

The extremely hard compound layer—compared to the base material—needs to be supported by the nitrogen-saturated diffusion layer giving a hardness profile, as shown in figure 6, to mitigate the risk of the so-called eggshell effect on soft substrates.

An additional requirement to produce highly reliable nitrocarburized cast iron components is a fast cooling from process temperature to minimize iron nitride precipitation. Iron nitrides are very brittle and promote flaking of the hard surface layer.

To present how Nitrex technology changes the mechanical properties of grey cast iron (GCI) brake rotors, four samples cut from rotors have been processed as shown on figure 7.

FIGURE 7: Rotor samples used for evaluation with 20 µm CLT

UNTREATED

NITREG®-C

NITREG®-C + ONC®

NITREG®-C + SMART ONC®

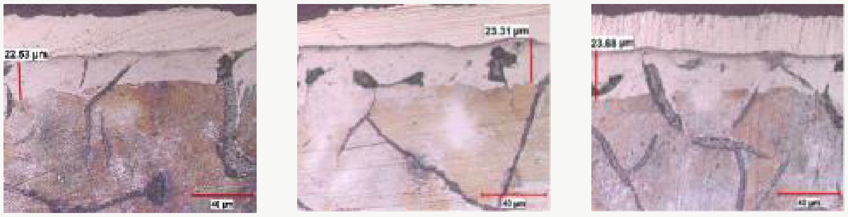


FIGURE 8: Compound layer of FNC samples

Table 2 displays the nitrided properties achieved by the processes given in table 1.

TABLE 1: Processes performed on rotor samples

No	TREATMENT
1	Untreated GCI
2	NITREG®-C
3	NITREG®-C + ONC®
4	NITREG®-C + SMART ONC®

TABLE 2: Nitrided properties of rotor samples

No	Compound layer thickness CLT (µm)	Oxide layer thickness OLT (µm)	Porosity (%)	Roughness Ra (µm)	Hardness (HV 1kg)
1	–	–	–	0.81	242
2	19-23	–	≤ 15	1.03	546
3	19-23	1-1.4	≤ 15	1.22	514
4	19-23	0.7-1	≤ 15	1.07	529

Corrosion tests in a salt spray chamber according to ASTM B117 (fig. 9) displayed that untreated rotor material (left) as well as FNC-only treated rotor material (right) already show heavy corrosion after 20 hours.

FIGURE 9: Corrosion on grey cast and FNC after 20 hours

Figure 10 shows specimens after 100 hours of oxidation (left) and smart oxidation (right) in a salt spray chamber. It can clearly be observed that smart oxidizing is providing the highest corrosion resistance of all samples.

FIGURE 10: Corrosion on ONC and smart ONC after 100 hours

NEWLY DEVELOPED NITREX SMART ONC® TECHNOLOGY ALLOWS FOR UNRIVALED CORROSION RESISTANCE

Over the last 10 years, Nitrex has performed an extensive research project into wear-resistant nitrocarburized, nitrocarburized, and post-oxidized surfaces on cast and steel parts. This optimized oxidation layer is toxic-free, and does not contain chromium, nickel, cadmium, lead, barium, or mercury. It can withstand up to 560 °C (1,040 °F) and still provides excellent corrosion resistance without crystallization or any decomposition during heat cycles.

While evaluating ASTM 117B test results on GCI rotors , 120 hours can pass before seeing a first corrosion spot on rotor material. In comparison, a traditionally post-oxidized grey cast iron additionally treated with a rust inhibitor, typically fails after 48 hours. Commercially available GCI rotors with rust inhibitor paint (premium black paint) and plain OE models showed less than 24 hours of salt spray corrosion resistance. As for a zinc and aluminum flake basecoat, it is claimed to take between 300 and 480 hours of salt water exposure before the rotors are totally corroded; rotors can last a bit longer if a topcoat is applied. Applying an electrophoretic coating with resin lasts 120 to 300 hours and a titanium grey finish provides 120 hours of salt spray protection.

Pin-on-disc testing with 20 N (fig. 11) shows that grey cast rotors treated with NITREG®-C have a higher coefficient of friction, stabilizing at 0.7, compared to untreated rotor material being somewhat stable at 0.42. All nitrocarburized samples show an almost identical behavior.

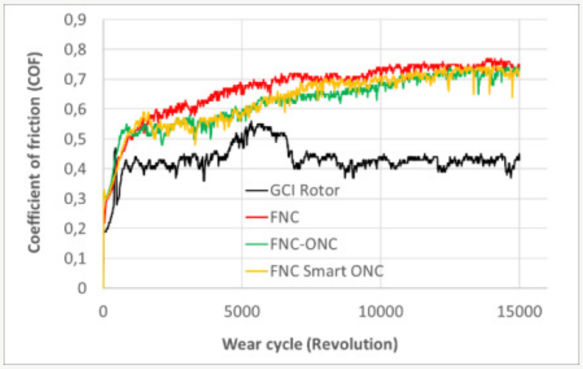


FIGURE 11: Evolution of coefficient of friction (20 N)

HIGH VOLUME REQUIRES HIGHLY AUTOMATED LIGHTS-OUT HEAT TREATMENT CELLS

According to Market Research Future (MRFR), a global market research company, the automotive disc brake market is projected to reach around USD 18 billion by 2025 [17].

TRW Aftermarket, a member of ZF Group, the world's leading supplier of safety-related vehicle parts and comprehensive service, states that it produces more than 12 million brake discs per year for vehicle manufacturers and the independent aftermarket around the world [18].

With FNC being an additional production operation to standard brake rotors today, the constant rise of production costs driven by factors, like direct and indirect labor, as well as gas and energy prices, will add a non-negligible share to the total cost of braking systems. Having this in mind, while at the same time considering the sheer volume of parts to be treated, requires the installation of highly automated production centers as shown in a typical layout displayed below.

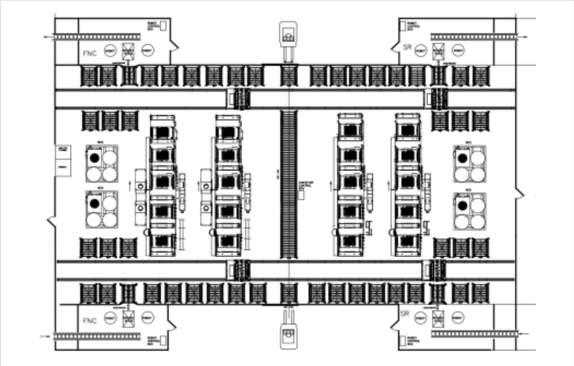


FIGURE 12: Automated SR and FNC line for high-volume production

Besides the automation level to keep up with the high production level, this also requires a technology able to produce the brake rotor protection layers reliably time after time.

Nitrex's approach to high-volume mass production offers specifically designed multi-chamber furnaces where loads up to 3 metric tons are moved through sealed chambers, each of them performing a different stage of the FNC process. Starting with pre-heating, activating and nucleation, the load will then move to a first FNC chamber, continue to a second FNC chamber before being transferred to optional ONC® and fast cooling.

CELL DESIGN AND FLOW THROUGH THE CELL

The cell is designed to operate so-called dry machined parts , which lets you skip the cleaning operation prior to FNC and/or SR. It is divided in two sections, nitrocarburizing (FNC) and stress relieve (SR). Parts enter the cell from below, they exit it on top of the schema, and they are delivered into and out of the cell using roller conveyors.

NITREX MULTI-CHAMBER FURNACE FOR HIGH-VOLUME FNC WITH THE ONC® OPTION.

FIGURE 13: Nitrex NXL continuous series

Incoming parts

Typically, the automated line starts with parts receiving. The cell has two entry points for parts equipped with two robots each, loading parts from mechanical production onto cell baskets. In this example, parts from mechanical production are placed one after another on a motorized roller conveyor and picked one by one by two robots, each of them fixturing the parts on opposite sides of a furnace rack. Once it is fully loaded, the rack will be picked up by one of the two charge cars and moved into the cell. If no furnace is immediately available, the rack will be placed on a magazine close to the most convenient furnace for an optimum workflow.

Loading the furnace

As soon as a furnace is ready to receive a new load, the charge car able to load within the shortest time will pick up the load from the magazine, move it to the furnace and load the first chamber. Along with loading the chamber, the scheduler is transferring the recipe suitable for the parts to the furnace control system. The control system starts the recipe.

Transit through the furnace

FNC and SR furnaces are designed as so-called multi-chamber furnaces. Each chamber can perform a different technological stage whereby the temperature, but even more importantly, the process atmosphere can be adjusted to the process flow. Both furnace types start with heating and equalizing the temperature, but they are also able to perform a first part of the thermal/thermochemical treatment. The following chambers continue the treatment whereby the second-to-last chamber in a FNC furnace is also able to perform a post-oxidation. The last chamber in both furnace types allows for a turbo cooling of the parts prior to unloading. Racks are moved through the furnace by a takt time adjusted to the technological needs given by the parts' specification.

Unloading the furnace

When a load finished the technological treatment and can be safely unloaded, the furnace sends a signal to the scheduler that then starts an unloading sequence, telling the most convenient car to pick up the load.

The car will then move the load to either an empty magazine space or directly deliver it to the next suitable unloading robot station.

Delivering parts back to mechanical production

Like for receiving, the cell also has two exit points equipped with two robots each, unloading parts from the cell baskets back to mechanical production.

Parts will be removed from the rack and placed on roller conveyor. Once a rack is fully unloaded, it will be picked up by a charge car and moved into the cell.

In the middle of the cell is located a motorized transverse line (roller conveyor). When a car places a rack on one side of the transverse line, the line will automatically move the rack to the other side. The moment the rack is in end position, the scheduler will place an order to a charge car to pick up the load and put it to a selected empty magazine space. This basket is now able to receive new parts.

Redundancy concepts for incident handling

Entry and exit points are equipped with two robots each. In case of one robot not being operational, the second robot will take over the task of the inoperable one. Therefore, the loading table between the robots can be rotated by 180°. Of course, this will slow down the loading and unloading operation but not stop production.

Entry and exit points for SR and FNC can handle racks destined to be loaded or unloaded from the other process line. This action is also supported by the transverse line.

At the two ends of the transverse line are manual ports to load and unload racks using a forklift. These entry points will also be used to initially load new racks into the cell and exchange worn-out racks.

The two tracks on the two sides of the heat-treating cell are holding two charge cars each. In case one of the charge cars is disabled, this car can be parked, allowing the functional car to handle all loads on this side.

SR and FNC lines are equipped with two identical furnaces each, allowing for a continuous production at a lower productivity but without stopping the entire production.

Bridging shifts without operators

The cell is designed to hold 50 racks allowing for a lights-out operation of up to 30 racks during non-working hours. This will allow for better productivity but also keep up overall production in case of an incident as described above.

MASTERING THE WORLD OF SURFACE TREATMENT

Nitrex is the only fully integrated solutions provider in the global surface treatment industry, with a worldwide presence in over 50 countries. Our integrated lines of business allow us to provide premium nitriding and vacuum turnkey furnaces, software & controls, clean processes through our heat-treating services in case of overflow or strategy change in your facilities, as well as aftermarket parts and support available within 24 hours. With more than 4,000 formulas, our portfolio is built on proven science and technology to enhance material strength and optimize performance.

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