

Applications and Design of Low Temperature Surface Hardened Stainless Steel Components in Automotive Applications

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ABSTRACT

While the excellent corrosion resistance of austenitic and duplex stainless steels has resulted in wide commercial application, poor tribological behavior, especially low abrasive/adhesive wear resistance and a tendency to fret, has prevented the use of these materials in applications where both corrosion and wear resistance are required. For more than 20 years low temperature carburizing or nitrocarburizing has offered a solution to enhance mechanical properties without altering the corrosion resistance. These thermo-chemical diffusion processes form carbon or nitrogen S-phase while avoiding carbide precipitation that causes sensitization. This paper presents application and design examples of low temperature carburized austenitic stainless steels in kinematic and static parts of automobiles. For example, kinematic components attached to the engine have to resist a relatively high corrosive loading in combination with temperatures exceeding 500°C. Furthermore these kinematics suffer from fretting fatigue on the bearing due to the vibration of an engine during its years of service. The galling, fretting, wear, and corrosion resistance of stainless steels equipped with Carbon S-Phase can withstand these forces. Especially in the automotive industry, a very reliable and reproducible solution is required and low temperature carburizing or nitrocarburizing fits the demand for cost efficient, durable, and corrosion resistant high volume components.

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INTRODUCTION

Global automotive megatrends are focusing on efficiency and CO₂ reduction. There is a massive effort of all OEMs to use lightweight materials, design more efficient engines, or switch over to hybrid cars. Stainless steel is neither lightweight nor necessary for an efficient engine. For a long period of time stainless steel was purely used for structural or decorative purposes, for example the stainless steel hood of the Rolls-Royce Phantom. In today's car, more and more stainless steel is used in technical components. Extensive use of stainless, mainly ferritic, was caused by new emission goals for the engine and thus high temperatures in a corrosive environment on the exhaust system. Components like the exhaust manifold, the piping and the muffler are made out of AISI409 stainless steel [16]. Additional applications include silencer wool for the exhaust system, hose clamps and seatbelt springs among many others [11]. The introduction of stainless steel for mechanical precision parts, e.g. for fuel supply, has become common. Even the more expensive Duplex stainless steels have entered the automotive mass market [7]. Functional components out of Duplex stainless steel can combine mechanical strength with extremely high corrosion resistance. The automotive industry is driven by more severe requirements concerning safety and higher efficiency of the vehicle.

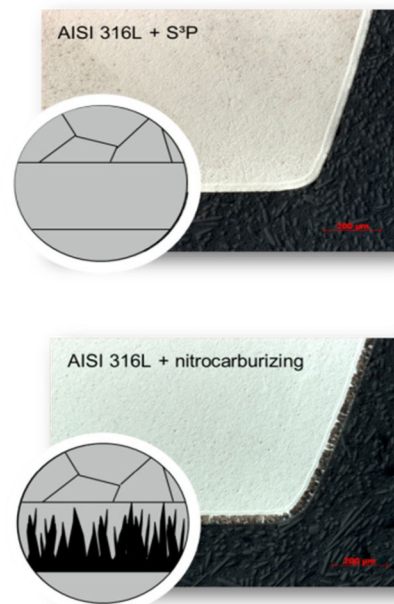


Figure 1. Microstructural differences between low and high temperature diffusion processes, top: S-Phase without precipitations, bottom: nitrides and carbides on the surface followed by a diffusion zone. Images taken at 100X.

Unfortunately stainless steels can be quite weak from a mechanical point of view. Low abrasive or adhesive wear resistance and a tendency for fretting have prevented the use of these materials in applications where both corrosion and wear resistance are required. Standard technologies like nitriding, nitrocarburizing or boriding are not an option as they would deteriorate the excellent corrosion resistance. This is where low temperature carburizing or nitrocarburizing has offered a solution to enhance mechanical properties without altering the corrosion resistance [3]. Suitable for almost every type of stainless steel, these thermo-chemical diffusion processes form carbon or nitrogen S-phase while avoiding carbide or nitride precipitation that can cause sensitization with a loss of both corrosion resistance and mechanical properties, [Figure 1](#). All these facts have already led to a variety of applications in the automotive industry [9].

LOW TEMPERATURE CARBURIZING OR NITROCARBURIZING

Low temperature surface hardening of stainless steel by introducing carbon or nitrogen into the surface has attracted quite extensive research among materials engineers. A good overview of the fields of research is given by Dong [2]. Another work focusing on low temperature carburizing has also found its way to the ASM handbook [10]. Since the conventional knowledge during the last century was that austenitic stainless steel cannot be properly hardened without losing the corrosion resistance, these treatments prove the opposite. Low temperature carburizing and nitrocarburizing allow a hardened case of more than 1000HV (Vickers Hardness) while maintaining the corrosion properties.

Applying a treatment temperature below a level where precipitates cannot form leads to the good corrosion resistance of the hardened zone but provides several challenges. The protective passive layer is quite stable at such low temperatures and thus would prevent the interstitial atoms from diffusing into the surface. A suitable activation or removal of the passive layer is the key for achieving uniform surface hardening. Such low treatment temperatures also prolong the time needed for a sufficiently thick case of 15 to 40 μm . But with high enough partial pressures for carbon or nitrogen a relatively quick supersaturation with the interstitials can be achieved. Supersaturation in this case means, that the typical solubility for carbon in AISI 316 is <0.015 at.% [12] and the maximum values achieved in Carbon S-Phase are about 12 at.%. This also means that the supersaturated layer is in para-equilibrium and thus metastable. It will decompose into more stable phases, nitrides or carbides, when heated above a certain time/temperature regime [12]. For every application it has to be taken into account that the long term stability of Carbon and Nitrogen S-Phase is at roughly 400°C and 350°C respectively. Short term stability reaches much higher values.

Due to the characteristics of diffusion there is a gradual hardness increase with the formation of massive internal compressive stresses caused by the massive supersaturation. The outcome is a significant improvement to the fatigue strength of the material [5]. On the

outermost surface these compressive stresses can reach more than 2GPa for carburized and more than 6GPa for nitrided 316L stainless steel [13].

Compared to low temperature nitriding, carburizing has several advantages. These advantages are a function of a lower driving force to create precipitates and a smoother transition from the hardened S-phase to soft, untreated material. The achievable diffusion depth without forming precipitates is improved and the allowable load bearing capacity to failure is significantly increased [12]. Also, the ductility of Nitrogen S-Phase at rapid loading is quite limited. This is why a combination of both processes was introduced, known as low temperature nitrocarburizing. By addressing some of the limitations, it combines the beneficial properties, like a hard surface and a smooth transition to the core. However, the fatigue strength and the high ductility of pure Carbon S-Phase is still at a much higher level. A hammer and nail test, simulating rapid loading with plastic deformation, reveals that Carbon S-Phase deforms uniformly without forming cracks, [Figure 2](#).

A summary of the differences between low temperature carburizing and nitriding is given by Bell and Zang, [Table 1](#).

Table 1. Characteristics of low temperature nitriding and carburizing, modified from Bell and Zang [12]

Characteristic	Carburizing	Nitriding
Treatment temperature	300°C – 550°C	300°C – 450°C
Typical layer thickness	5 – 40 μm	2 – 20 μm
Layer structure	Carbon S-Phase	Nitrogen S-Phase
Corrosion resistance	Good	Good
Surface hardness	900 – 1100 HV0.05	1400 – 1600 HV0.05
Hardness profile	Gradual change	Abrupt change
Wear resistance	Good	Very good
Layer toughness	Good	Poor
Load bearing capacity	High	Low
Fretting fatigue property	Good	Very good
Plain fatigue property	Very good	Good

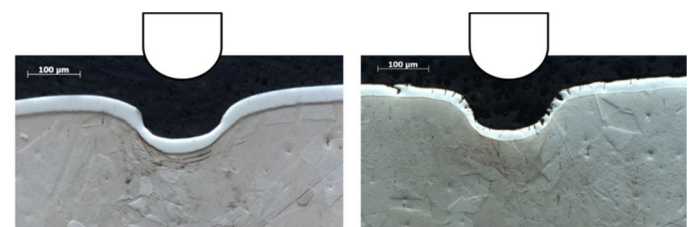


Figure 2. Microsection after hammer & nail test, left: low temperature carburized S-Phase deforms in a ductile manner, right: low temperature nitrocarburized case acts brittle and shows cracks

APPLICATION EXAMPLES

The properties of stainless steel equipped with S-Phase can combine corrosion-, wear-, galling-, fretting- and cavitation resistance. Further the diffusion layer offers a key advantage, that the risk of delamination is avoided. This is also beneficial with regards to both pressure and thermal shock resistance. The Carbon S-Phase remains ductile during rapid loading despite having a hardness of greater than 1000HV, which is a unique characteristic for such hard surfaces. All these features give rise to plenty of applications in the engineering field.