HOW TO IMPROVE MACHINING PRIOR TO LOW TEMPERATURE SURFACE HARDENING

REPRODUCIBLE RESULTS

INCREASED SURFACE HARDNESS

HIGHEST CORROSION RESISTANCE

IMPROVED DIFFUSION DEPTH

MINIMISING THE INFLUENCE OF MACHINING FOR OPTIMAL RESULTS

Bodycote S³P, featuring the proprietary processes Kolsterising® and S³P ADM, are a group of commercially available low temperature surface hardening (LTSH) processes. With these processes it is possible to achieve a hard (> 1 000 $HV_{0.05}$) and wear resistant surface on stainless steel components, whilst maintaining superior corrosion properties. Surface hardening is usually performed after the final machining step and is one of the last production steps before a component is serving an application. Optimal results concerning hardness, diffusion depth and corrosion resistance are only achievable with correct choice of machining parameters, optional surface finishing and/or heat treatment prior to LTSH processes. This overview provides guidance on machinability of stainless steels and considerations for the optimal machining parameters for stainless steel grades.

Machinability of stainless steels

Machinability is rated on total machining time, tool life and the surface finish of the product. It is the task of the machine shop to find the correct parameters in order to provide a uniform and reproducible surface finish with reasonable costs (tool life and time). For stainless steels in particular the surface finish is highly influential on the corrosion properties. A smooth and uniform surface without crevices or scratches is considered to be optimal. The machinability of stainless steels is significantly different from machinability of mild steels. Austenitic and duplex stainless steels in particular are known to be difficult to machine. Machinability is negatively influenced by the tendency to work harden, poor thermal conductivity, high toughness and cold welding behaviour.

Deformation martensite

In particular, the tendency to work harden leads to the generation of deformation martensite on machined surfaces. In general, higher cutting forces lead to more deformation martensite. Also, forming processes can lead to an excessive formation of deformation martensite. Deformed surfaces have a negative influence on diffusion processes such as Kolsterising® and S³P. Diffusion depth and hardness can be lower. Additionally, reduced corrosion resistance can occur. Austenitic stainless steel can become magnetic, an unwanted side effect for many applications. It is possible to directly measure the amount of deformation martensite with specific ferrite measuring devices. The amount of unwanted deformation martensite can be reduced by certain heat treatment and surface modification techniques, presented in this overview.

Sulfide-containing alloys are not an option when high corrosion resistance is needed

In order to improve machinability, a certain amount of sulfur can be alloyed to stainless steels, however this measure is not recommended as sulfur forms manganese sulfide stringers in the material. These are not only a weak spot for chip, but also for corrosive attack. If a sulfide stringer is present on the surface of a machined part, the protective passive layer formation will be hindered in this area. Corrosive attack is more likely in a corrosive environment. The corrosion resistance of these machining grades is significantly lower than the resistance of standard alloyed austenites. Therefore such grades are not suited for applications in corrosive environments. Additional information on the influence of sulfur on corrosion resistance is given in a dedicated 'Spotlight', (S³P: Consideration regarding sulfur in corrosion-restistant steels).

Machining processes influence the results of low temperature surface hardening

The following pages summarise the influence of different machining processes on the results of low temperature surface hardening techniques, such as Bodycote's S³P processes (Kolsterising® and S³P AMD). For optimal results alloys with low sulfur content and optimised machining parameters should be considered. Tools which are used for the machining of unalloyed steels should not be used for machining of stainless steels, as contamination cannot be avoided. Additional post-processing methods might be applied when necessary.

MACHINING WITH GEOMETRICALLY DEFINED CUTTING EDGE

Turning and Milling

Stainless steels, especially austenitic and duplex grades, tend to form a built-up edge during machining. Due to the poor thermal conductivity of stainless steels, additional heat build-up is expected. In order to achieve optimal results after low temperature surface hardening the following points should be considered*:

- Compared to carbon steels, higher forces are needed to machine stainless steels. Therefore the machine should be sufficiently designed to machine stainless grades.
- Tooling and fixtures should be as rigid as possible in order to prevent vibration which would lead to an uneven surface finish.
- A positive feed rate should be maintained during the complete processing cycle, in order to prevent excessive cold working.
- Lower cutting depth will lead to a reduction of cold working effect on the surface.
- Lower cutting speeds should be considered, as excessive speeds lead to higher tool wear, a poorer surface finish and early tool replacement.
- Tools must be kept sharp to minimise friction between tool and chip. A sharp cutting edge produces the best surface finish.
- The use of cutting fluids, specially designed for stainless steels, is recommended. As stainless steels are a poor thermal conductor cooling is necessary.

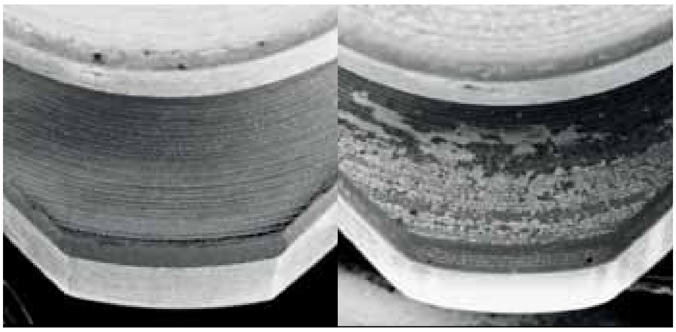


Fig. 1: Turned stainless steel surface. Left: sharp tool and adjusted machining parameters lead to a regular surface finish. Right: worn tool and high cutting forces lead to smearing of the surface/ irregular finish with reduced corrosion resistance, flaking and poor diffusion behaviour.

With these facts in mind, it is possible to achieve a good surface finish and minimise cold working (deformation martensite) which will ultimately lead to:

- Higher diffusion depth with an increase in lifetime
- Higher surface hardness (as more carbon/nitrogen can be dissolved)
- Maintained or even improved corrosion resistance

If a good machining practice does not lead to sufficient results after low temperature surface hardening (LTSH), additional post processing, like solution annealing and/or electropolishing should be considered prior to treatment. Fig. 1 shows the influence of tool wear on results after a LTSH process.

* *Source: Thyssen Krupp VDM "Verarbeitungshinweise für austenitische Edelstähle und Nickelbasislegierungen"*

POST-PROCESSING AFTER MACHINING

Residues from previous processes, as well as an influenced surface, make it necessary to apply certain post-processing methods after machining and before surface hardening. Not all of these measures are mandatory, but many are recommended.

Chemical cleaning, de-greasing, pickling

Chemical cleaning and de-greasing is a mandatory process step after all machining processes and prior to any heat treatment operation (incl. low temperature surface hardening). Clean and smooth surfaces are a key factor for unhindered diffusion of carbon and/or nitrogen into the part's surface.

- Residues from previous production steps may act as a diffusion inhibitor, lowering diffusion depth and surface hardness.
- Furthermore, residues may lead to stains after treatment, which cannot be removed in all cases.
- Iron particles can lead to localised corrosive attack (flash rust)

Additional pickling, de-scaling and / or passivation can be necessary in order to further improve corrosion properties of machined parts. With pickling, for example, it is possible to remove deformation martensite which was formed in previous machining steps.

Heat treatment

Depending on the stainless steel grade and the intended application, a heat treatment process prior to low temperature surface hardening can be necessary:

- Additional solution annealing of austenitic and Ni-based alloys can be an option to improve corrosion behaviour of surface hardened parts.
- Martensitic and precipitation hardening (PH) grades should be in heat treated condition (aged or hardened).

Mass finishing

Mass finishing processes can include tumble finishing or vibratory finishing. Both are cost effective methods to clean, dry, de-burr or polish machine parts. As stainless steels are relatively soft, parameters should be adapted to those materials, in order to achieve a good surface finish and low deformation martensite formation. The influence of vibratory finishing parameters on the surface of stainless steel parts is shown in Fig. 2.

- In general the finishing time should be short.
- Used compounds and/or abrasives should be rather soft.
- Dedicated machines and additives are recommended for processing of stainless steels to prevent ferritic contaminations, which would lower corrosion resistance.
- After finishing, proper cleaning and drying should be considered in order to maintain corrosion properties. Residues from finishing or drying processes such as compound, abrasives or organic materials further inhibit diffusion during low temperature processes.

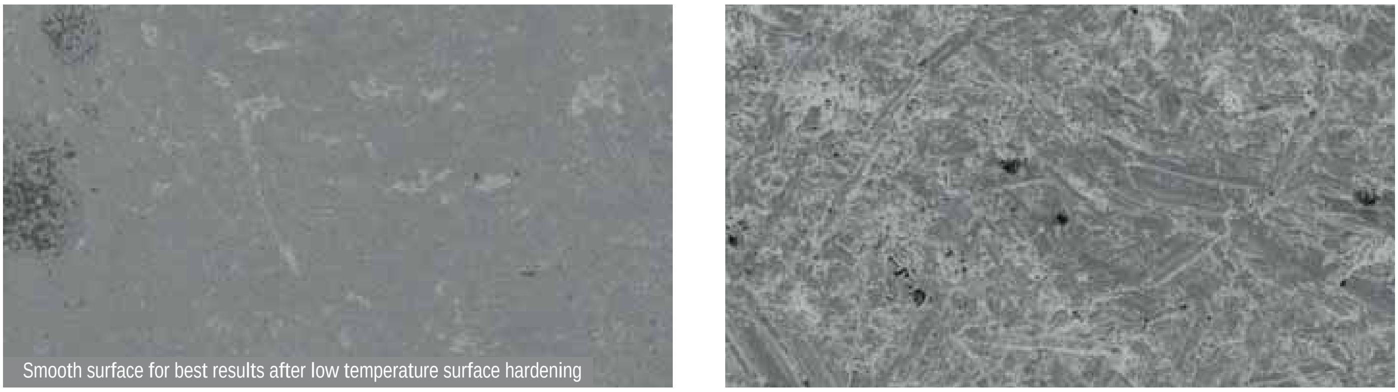
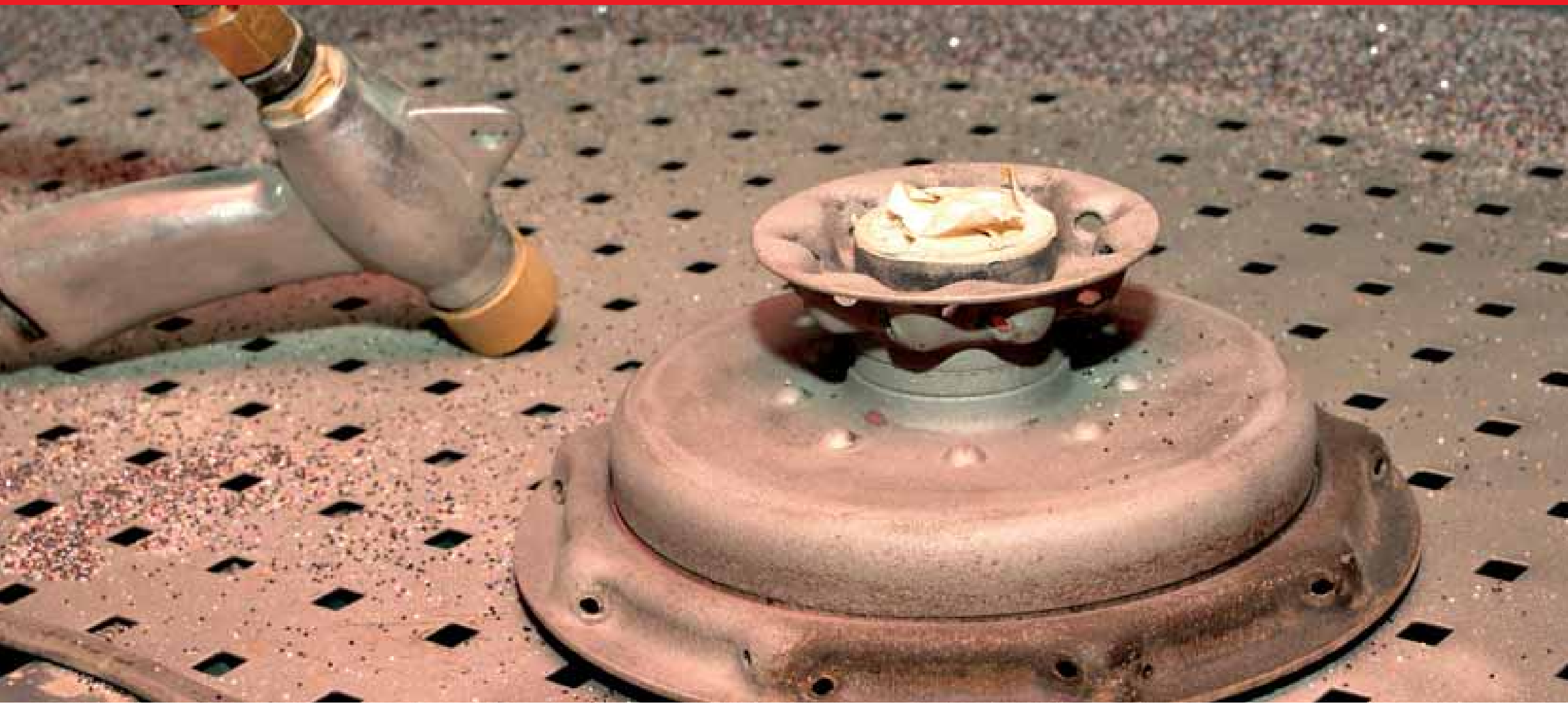


Fig. 2: Stainless steel surface after vibratory finishing. Left: smooth surface (Ra 0.17) with little defects, achieved with adjusted parameters and soft abrasives. Right: coarse surface finish (Ra 0.56), abrasive inclusion and excessive formation of deformation martensite, which leads to poor corrosion and diffusion behaviour.



Electropolishing

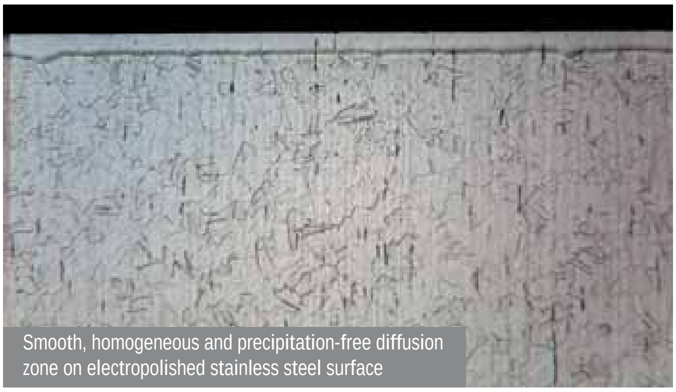
Electropolishing as a final step prior to low temperature diffusion processes can improve the surface finish of machined parts significantly.

- Micro peaks and valleys on the surface are smoothened.
- Highly influenced surface regions (up to 50 µm) can be removed, leading to an unhindered diffusion of carbon and/or nitrogen atoms into the surface. Surface hardness and diffusion depths can be increased.
- The result is usually a higher corrosion resistance and more appealing optical appearance.

Blasting

Blasting, especially sand blasting, is not recommended for stainless steel components if highest corrosion resistance is needed. Fig. 3 shows the influence on the surface quality and diffusion result of blasting and electropolishing of an AISI 316L prior to low temperature surface hardening.

- After blasting surface roughness is significantly higher, leading to a higher probability of attack in a corrosive environment, for example chlorides may aggregate in the formed pits and grooves.
- Residual abrasives can get stuck in these grooves, and further promote corrosive attack.
- High forces during these types of processes lead to an excessive formation of deformation martensite on the surface, leading to non-uniform diffusion results.



Smooth, homogeneous and precipitation-free diffusion zone on electropolished stainless steel surface

Rough surface and non-uniform diffusion zone after sand blasting leading to significantly lower corrosion resistance and poor mechanical behaviour

Fig. 3: Comparison of LTSH results for AISI 316L after electropolishing (left) and sand blasting (right). Sand blasting leads to local high deformations with excessive formation of deformation martensite. Diffusion is hindered and corrosion resistance is lowered. In comparision, the electropolished surfaces lead to a defect-free and homogeneous diffusion zone.

MECHANICAL FINE MACHINING

Grinding and honing

The need for mechanical fine machining derives from tight tolerances which are needed in certain technical applications. Grinding and honing are machining methods with a geometrically undefined cutting edge. Material removal is generated by abrasives, eg. Al_2O_3 or SiC, bound in a grinding wheel or honing stone respectively. With the right process parameters and abrasives, fine surface finishes are achievable. The surface finish has a high influence on corrosion properties and diffusion behaviour. With high forces more deformation martensite is formed, which impairs diffusion results on ground and honed parts. As a result, corrosion resistance can be significantly lowered. Therefore it is very important to adjust grinding and honing parameters to stainless steels, especially if surface hardening after machining is necessary.

- Pressures and cutting forces should be as low as possible in order to lower the formation of deformation martensite and reduce excessive heating of the surface. As thermal conductivity of stainless steels is low, proper cooling is necessary.
- Tools should be free of iron and chlorides.
- Sharp tools should always be used. Otherwise the machined part will heat up and the surface becomes pushed and smeared instead of cut, which increases the risk of lowered corrosion resistance. Even delamination of the massively deformed surface region is possible.
- Additional post-processing (e.g. electropolishing) and/or annealing should be considered prior to the S³P process for optimal results.

Fig. 4: Honed stainless steel surface. Right: High cutting forces and a worn tool lead to a surface which is rather deformed than cut. Left: low forces and sharp tool lead to distinct grinding patern, which is natural for correct honing operations. Less deformation, heat input and smearing lead to better diffusion behaviour and improved corrosion resistance.

FORMING AND CUTTING

Stamping and drawing

Stainless steel sheet metals are often formed by deep drawing or stamping operations. Due to the tendency to cold working, high deformation grades lead to an increased strength and hardness of the material. If deformation rates are too high, one or more annealing steps are necessary to relieve the induced stresses. Otherwise the deformed sheet metals may crack. Additionally, high deformation rates ultimately lead to an excessive amount of deformation martensite on the surface, which impairs diffusion behaviour and negatively influences corrosion properties after low temperature surface hardening. For optimal results after low temperature surface hardening, for drawn or stamped parts the following guidelines should be taken into account:

- Annealing is recommended if the increased strength due to deformation is not needed.
- Due to work hardening of stainless steels, higher pressures are needed for drawing and stamping.
- Due to stainless steel's tendency to galling, friction has to be as low as possible during forming operations. This can be achieved by proper lubrication and die coating.

Blanking and punching

Instead of time consuming machining, punching and blanking can be a quick and cost effective method to produce geometrically simple parts of specified dimensions, especially in mass production.

- Depending on the method chosen, post-processing and deburring might be necessary. Burrs and surface irregularities occur in the so-called fracture zone. In this area material is stripped and smeared rather then cut. Stainless steel properties lead to some constraints, which have to be taken into account.
- The tendency to galling requires tool coating and proper lubrication. Due to cold working, cutting / punching forces are significantly higher compared to carbon steels.
- The high toughness of stainless steels can lead to smearing and overlapping of material in the cutting zone. This not only leads to the excessive formation of deformation martensite, but also to crevices which can be a weak spot for corrosion.
- An option to improve the surface quality after blanking is fine blanking. This method improves surface quality. Post processing might be skipped, which can offset the higher tooling costs.

Fig. 5 shows the fracture zone after punching and subsequent low temperature surface hardening (left). High deformation and poor surface quality in the fracture zone lead to lower diffusion depth.

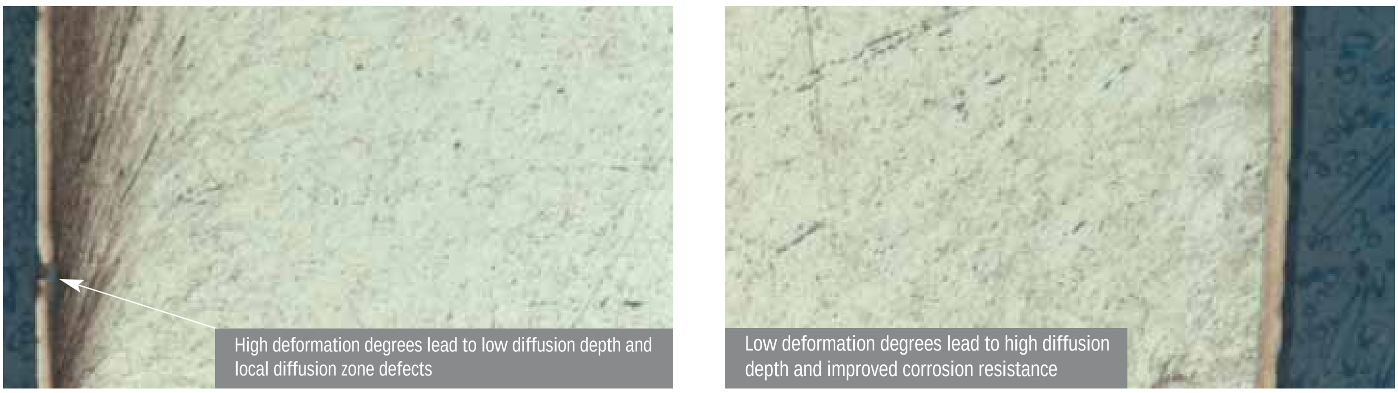


Fig. 5: Surface hardened stainless steel component. Left: Punched surface. Irregular and heavily deformed (dark areas) surface. Lowered diffusion depth and impaired corrosion properties in this zone. Right: same part bored instead of punched. Less deformation and regular surface finish lead to higher diffusion depth and improved corrosion properties.

CASTING AND POWDER BASED PROCESSES

Casting

Different casting methods such as sand casting and die casting can be used to form complex parts, with complex inner dimensions, in one process step. However the surface quality in the as-casted condition is often not sufficient for technical applications and post-machining is necessary.

- Impurities in the surface or the bulk after casting can lower corrosion and mechanical properties compared to a forged material with comparable composition. Inclusions of slag or sand on the surface can also negatively influence corrosion resistance.
- Due to rather slow cooling rates the formation of a partially ferritic structure (δ-ferrite) is possible. If δ-ferrite content exceeds 3 vol % a negative influence on diffusion behaviour and corrosion resistance is expected. It is possible to reduce the δ-ferrite content after casting with additional heat treatment, if necessary.

Additive Manufacturing methods

Additive Manufacturing (AM) methods, such as metal injection moulding (MIM) and Selective Laser Melting (SLM) are relatively new production methods based on powder metallurgy. All processes from this group are in principle suited for processing stainless steels. While MIM processes are suitable for large lot sizes, SLM based processes are suitable for producing parts with lot size one.

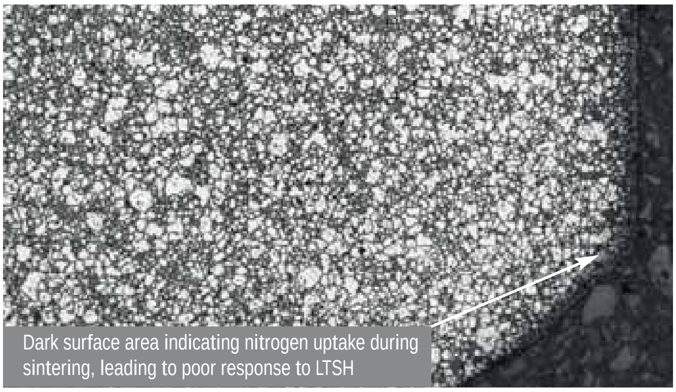
MIM processes are comparable to polymeric injection moulding processes. Metallic powder is mixed with a polymeric binder and formed with injection moulding machines. After the moulding process, the binder has to be removed and the metallic powder has to be bound by sintering in a furnace under vacuum or shielding gas.

- The used shielding gas can have an influence on results if a MIM part should be Kolsterised.
- Typical gases are a mixture of hydrogen and nitrogen (H_2/N_2) which form a reducing atmosphere in order to prevent oxidation. In some cases the nitrogen might diffuse in the surface of the sintered part, hindering further diffusion during LTSH.
- If nitrogen is problematic during sintering, a vacuum atmosphere shall be considered.

Fig. 6 shows a sintered part with an influenced surface by nitrogen diffusion in a H_2/N_2 atmosphere. A subsequent boring operation (right picture) removed the influenced surface. In this area unhindered diffusion is possible.

Selective laser processes are a group of processes to produce parts out of a powder bed with a laser beam. Parts are built-up layer-by-layer leading to nearly no geometrical constraints. A downside is the relatively poor surface quality, which create a need for post-processing. Additionally, optimal process parameters have to be found for a low amount of porosity.

- Pores can reduce mechanical properties and corrosion resistance as they act like crevices.
- Outer porosity and surface imperfections can be reduced by adjusted post-processing.
- Inner porosities can be closed by hot isostatic pressing (HIP). With such processes mechanical strength is further increased.



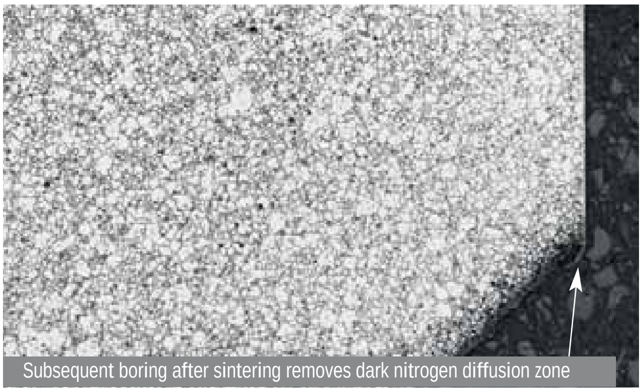


Fig. 6: Cross section sintered, stainless steel MIM parts. Nitrogen diffusion (dark surface area) prevents unhindered diffusion and high surface hardness after LTSH. A subsequent boring operation (right) removes the nitrogen diffusion zone partially. Unhindered diffusion is possible in this region.

www.bodycote.com

12.2018/EN 422-2012