

Effects of shielding gas on laser surface processing

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Laser surface processing is widely used in modern manufacturing to enhance surface properties such as roughness and oxidation resistance. In this thesis, laser surface processes are defined to be low-power processes such as laser polishing, laser cleaning and laser engraving. A key factor that influences the outcome of these processes is the selection and control of shielding gas. Shielding gas controls oxidation, stabilizes the melt pool, and directly influences the final surface quality and the mechanical properties of the processed material. This thesis presents a comprehensive literature review on the effects of various shielding gases including argon, nitrogen, oxygen, carbon dioxide, and compressed air on laser-based surface treatments.

The findings show that inert gases like argon and nitrogen offer the best performance in oxidation prevention and surface quality, making them suitable for precision applications. Reactive gases such as oxygen and carbon dioxide increase material removal rates, but they introduce surface roughness and oxidation-related defects. Compressed air is a cost-effective alternative for applications where surface roughness and oxidation are not critical.

In addition to gas type, the study highlights the importance of gas flow parameters and delivery methods. Variables such as flow rate, pressure, nozzle distance, and shielding approach (chamber vs. nozzle) have a substantial effect on surface quality because they determine the stability, coverage, and effectiveness of the shielding gas, directly influencing melt pool behavior, oxidation prevention, and the formation of surface defects. Proper optimization of both gas selection and the method of introducing gas to the object is essential for achieving high-quality results in laser surface processing.

Key words: Shielding gas, laser surface processing, laser polishing, gas flow, chamber shielding, nozzle shielding,

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1 Introduction

Laser surface processing is gaining more attention in modern manufacturing due to its ability to modify materials with high precision and efficiency (Lu et al., 2024; Xu et al., 2023). This thesis studies laser surface processing applications such as laser polishing, laser cleaning, and laser engraving. These processes play a crucial role in enhancing surface integrity, wear resistance and aesthetic properties because they directly modify the microstructure and smoothness of the surface layer (Wang et al., 2023). The outcome of these processes depends on the choice of shielding gas or ambient gas, which directly affects oxidation prevention, surface roughness and microstructural modifications. (Ermergen et al., 2023; Temmler et al., 2020)

The selection of different shielding gases such as argon, nitrogen oxygen, carbon dioxide, compressed air or propane has an impact on the surface characteristics of the processed material. Inert gases like argon and nitrogen prevent oxidation and produce smoother finishes. Reactive gases like oxygen and carbon dioxide enhance material removal rates but may introduce unwanted surface defects (Lu et al., 2024; Xu et al., 2023). Compressed air is a cost-effective alternative for laser cleaning applications (Maharjan et al., 2020).

This thesis aims to provide a comprehensive literature review on the role of shielding gases in laser surface processes, analysing the effects of surface morphology and oxidation resistance. Special emphasis will be placed on different gases and their effects, the influence of the direction of the shielding or ambient gas, and the effects of gas parameters.

2 Different shielding gases and their effects

2.1 Argon

Argon is one of the most widely used shielding gases in laser surface processes due to its inert nature. Oxidation is a major factor in laser surface processing and argon is a suitable gas to introduce atmospheres that are not fit for oxidation. Oxide layers on the surface of the material can create rough spots and defects if they are formed during the melting and solidification process. Argon can minimize surface roughness during laser polishing by preventing oxides from forming. This has been observed in for example stainless steel AISI410 and Ti6Al4V titanium alloy (Lu et al., 2024; Wang et al., 2023).

In laser polishing applications, multiple studies (Ćwikła et al., 2021; Liang et al., 2020; Rosa et al., 2015; Ukar et al., 2015) have demonstrated that argon shielding improves the surface quality by minimizing oxidation and stabilizing the melt pool behavior. In laser polishing of Ti6Al4V parts (Liang et al., 2020) reported a reduction in surface roughness from 10.2 μm to 2.1 μm while polishing in an argon atmosphere compared to air. Similarly, in another study (Ćwikła et al., 2021) a surface roughness of approximately 2 μm was achieved on laser polishing of Inconel 718 by using local argon shielding. Ćwikła et al. (2021) compared air and argon and concluded that argon yielded much smoother, less oxidized surfaces on components. Rosa et al., (2015) further supported these findings by showing that surface roughness could be decreased by up to 85% using argon shielding in laser polishing of additive manufactured surfaces. Ukar et al., (2015) also emphasized that argon, combined with optimized laser parameters and scanning strategies, contributed to uniform surface finishes on tool steels. This difference between argon and oxygen is clearly demonstrated in Figure 1, adapted from wang et al., (2023), which shows that the surface polished with argon is much smoother than the surface polished with air. These results confirm that argon is effective in protecting against thermal oxidation and improving the quality of the laser polished surface, especially in oxidation-sensitive materials (Ćwikła et al., 2021; Liang et al., 2020; Rosa et al., 2015; Ukar et al., 2015)

Figure 1 shows the measured surface roughness profiles comparing argon-shielded and air-polished samples. The profile demonstrates that argon shielding results in a smoother surface, confirming its superior oxidation prevention

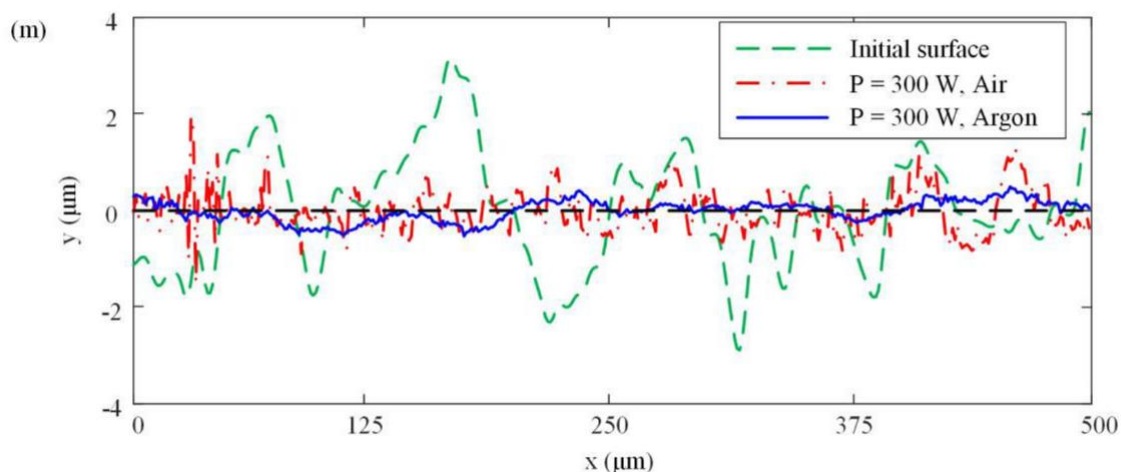


Figure 1. Line profiles of laser polished surfaces by using argon and air. Adapted from (Wang et al., 2023)

Maharjan et al., (2020) also found that argon provided better hardness and reduced oxidation in AISI 1020 steel compared to air. The overall microstructure of the parts was similar, but argon minimized oxide spalling and helped retain alloying elements at the surface, improving hardness slightly over air-hardened samples (Maharjan et al., 2020). Argon atmosphere reduces crack formation during laser polishing by maintaining a stable melt pool and preventing brittleness induced by oxidation. This was particularly noted in Ti6Al4V titanium alloy (Lu et al., 2024). In cast iron laser treatments, argon has been found to reduce surface oxidation and improve microstructural uniformity during laser hardening processes (Maharjan et al., 2020).

In laser surface patterning of 304 stainless steel, argon was used to control the Marangoni flow within the melt pool, resulting in more consistent surface features and smoother microstructures. Compared to air, the value of surface roughness of the patterned surface decreased by 86.2% when argon was used. This reduction was linked to the absence of oxide films that typically increase surface irregularities (Wang et al., 2023).

In laser engraving processes, argon was found to enhance the clarity and precision of engraved features. The inert atmosphere prevents surface oxidation, which often causes discoloration and reduces contrast in laser-marked areas. In tests on Cr12Mov steel, argon shielding produced the clearest, highest-contrast markings compared to compressed air or oxygen environments. Figure 2 shows how gas choice influences microstructural development.

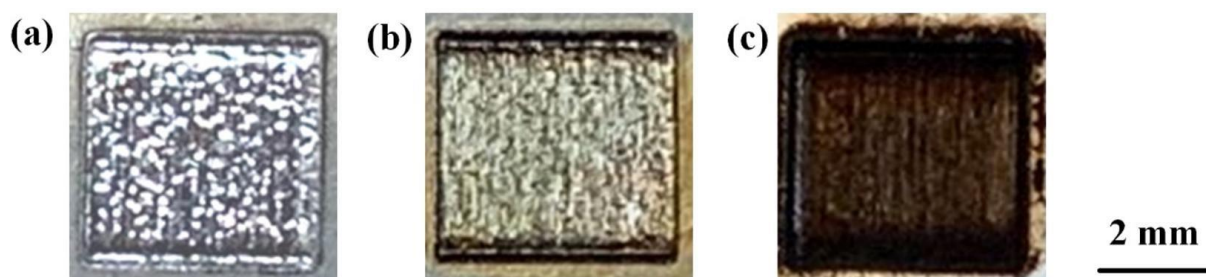


Figure 2. Images of the engraved surfaces under argon (a) compressed air (b) oxygen (c). (Xing et al., 2021a)

As figure 2 illustrates, argon shielding maintains a finer, more uniform microstructure, while air exposure leads to oxidation layers and surface defects. The macroscopic morphology under the argon atmosphere was bright (figure 2 a). The surfaces turned brown and black with compressed air and oxygen (figure 2 b and c) due to the chemical reaction during laser engraving. The material removal depth was significantly worse with argon compared to oxygen and compressed air with ~64% deeper laser engraved regions with air. (Xing et al., 2021a)

In laser cleaning, inert properties of argon are beneficial in removing contaminants without introducing oxidation or altering the base material. The use of argon ensures that sensitive materials, like titanium alloys, retain their integrity after cleaning them (Lu et al., 2024). Lu et al. observed that argon not only prevented surface oxidation but also minimized the formation of surface cracks during laser cleaning of titanium alloys (Lu et al., 2024). Explicit studies on laser cleaning and laser rust removal were limited, but the ability of argon in to prevent oxidation during laser polishing also makes it highly effective in rust removal applications. (Xu et al., 2023)

2.2 Nitrogen

Nitrogen is a cost-effective alternative to prevent oxidation in various laser surface processes. In laser-polishing of grade 2 titanium, nitrogen was found to limit oxidation and improve surface smoothness if used with correct parameters (Ermergen et al., 2023; Giorleo et al., 2015). Nitrogen is proved to improve microhardness and reduce surface oxidation particularly in cast iron (Maharjan et al., 2020). Research has also proved that nitrogen can perform comparably to argon in many cases by offering a similar level of oxidation prevention and surface quality improvement (Temmler et al., 2020; Xu et al., 2023). In laser polishing of

stainless steel, nitrogen reduced oxidation effectively and maintained good surface integrity even under varying flow rates (Wang et al., 2023; Xu et al., 2023)

A comparative study on laser micro-polishing revealed that argon and nitrogen exhibit significantly different effects. Argon primarily prevents oxidation without chemically interacting with the material surface. This ensures more predictable surface morphology, lower defect formation, and uniform mechanical properties. However, Temmler et al., (2020) found in a study that argon shielding alone is less effective in reducing surface roughness compared to nitrogen. In some cases, nitrogen achieved up to 85% surface roughness reduction. (Temmler et al., 2020).

Nitrogen's low reactivity can sometimes enhance the surface hardness in specific applications, such as laser hardening of steels. The ability of nitrogen to simultaneously prevent oxidation while modifying surface properties makes it a versatile choice for many industrial laser surface processes. (Maharjan et al., 2020)

Further supporting the benefits of using nitrogen as a shielding gas, Avilés et al., (2014) demonstrated that laser polishing of AISI 1045 steel in a nitrogen atmosphere resulted in surfaces with significantly fewer oxides, micro-cracks, and porosity than those polished in air. Nitrogen shielding preserved compressive residual stresses up to 200 MPa near the surface and helped retain favorable martensitic-ferritic microstructures, which improved fatigue life. While the surface roughness ($-0.33 \mu\text{m } Ra$) was comparable to air-polished samples, the oxidation-free nitrogen atmosphere contributed to more consistent mechanical properties (Avilés et al., 2011, 2014)

2.3 Oxygen and compressed air

Oxygen is generally avoided in processes where oxidation is detrimental to the quality of the product, but it can still be used strategically. Compressed air and oxygen are usually used in processes where a high material removal rate and low costs are beneficial. Compressed air is often used in laser engraving because of its active nature. The oxygen in compressed air promotes exothermal chemical reactions increasing the material removal rate. However, it causes higher roughness compared to inert gases such as argon. In Cr12MoV steel, the surface roughness with compressed air was $3.13 \mu\text{m}$, compared to $2.52 \mu\text{m}$ with argon. Compressed air caused higher material removal rates but led to higher oxidation of the work surface, which resulted in the need of post-polishing treatments (Xing et al., 2021b).

In laser polishing, compressed air caused oxidation, ultimately leading to a black oxide film that increased value of roughness noticeably. In case of stainless-steel surfaces polished with compressed air had a roughness of 0.35 μm , while surfaces cleaned in an argon atmosphere had a roughness of 0.16 μm . The use of compressed air also caused noticeably higher bulge formation on the material surface compared to argon. With compressed air, the bulges on the surface reached up to 22.6 μm while in an argon atmosphere the bulges only reached 5.6 μm . (Wang et al., 2023; Xu et al., 2023)

Laser polishing in an oxygen-rich environment also impacts fatigue life negatively. Polishing AISI1045 steel in ambient air resulted in Fe oxide layer formation, which introduced micro-cracks and inclusions that decreased fatigue strength. The oxides created crack initiation sites that led up to a 30% reduction in fatigue performance. Compared to nitrogen, oxygen exposure caused greater scatter in fatigue life and less consistent mechanical results. (Avilés et al., 2011)

2.4 Carbon dioxide

Carbon dioxide is rarely used in laser surface processes due to its high tendency to facilitate oxidation. In the studies, carbon dioxide has been used in laser polishing particularly titanium and stainless steel. Carbon dioxide promotes surface oxidation, which results in a rougher surface compared to inert gases. In titanium alloy polishing, carbon dioxide has been noticed to increase brittleness and compromised surface integrity due to enhanced oxidation. (Lu et al., 2024; Wang et al., 2023). In laser engraving active gases, like oxygen and carbon dioxide can enhance the material removal rate but at the cost of surface quality. This makes it suitable for rough machining but less ideal for finishing (Xing et al., 2021b)

2.5 Comparison of shielding gases in laser surface processing

Table 1 lists the properties and typical uses of shielding gases discussed in this thesis, helping compare their suitability for different applications.

Table 1. Comparison of shielding gases used in laser surface processing in terms of oxidation prevention, surface quality, cost and typical applications. Adapted from (Avilés et al., 2011, 2014; Ćwikła et al., 2021; Ermergen et al., 2023; Liang et al., 2020; Lu et al., 2024; Maharjan et al., 2020; Temmler et al., 2020; Wang et al., 2023; Xing et al., 2021b; Xu et al., 2023)

Gas type	Level of oxidation	Surface roughness after treating	Cost of Gas	Typical use	Reference
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Argon	Low	Very Low	High	Laser polishing, Laser cleaning	(Ćwikła et al., 2021; Lu et al., 2024; Temmler et al., 2020; Wang et al., 2023)
Nitrogen	Low-moderate	Low	Medium	Laser polishing	(Ermergen et al., 2023; Giorleo et al., 2015; Maharjan et al., 2020)
Oxygen	High	High (rough)	Low	Laser engraving, Laser cutting	(Wang et al., 2023; Xing et al., 2021a; Xu et al., 2023)
Carbon dioxide	High	High	Low	Rough treatments	(Lu et al., 2024; Wang et al., 2023; Xing et al., 2021a)
Compressed air	High	High	Very Low	Low-cost laser cleaning	(Wang et al., 2023; Xing et al., 2021a; Xu et al., 2023)

As it can be seen from Table 1, argon and nitrogen are preferred for polishing, while oxygen and carbon dioxide are more suited for material removal tasks. The choice of shielding gas is critical in determining the effectiveness of laser surface processes such as polishing, cleaning and engraving. Gases like argon and nitrogen consistently demonstrate superior performances in oxidation prevention and surface quality due to their inert properties. Argon is most commonly regarded as the most stable and effective shielding gas. It produces the smoothest surfaces and minimizes oxide formation in oxidation sensitive materials such as different steels. Nitrogen offers a more cost-effective alternative with similar benefits in many applications, especially in cast iron and medium carbon steels.

On the other hand, reactive gases like oxygen, carbon dioxide and compressed air promote material removal, through reacting with the laser. Reactive gases tend to induce oxidation which compromises surface integrity and leads to higher roughness, discoloration and decreased fatigue strength. Compressed air is economically attractive, but it offers limited shielding capability and often results in oxidation-related defects, making it less ideal for high-precision tasks. These gases are more suitable for laser engraving or laser cutting, where high removal rates are desired, and surface aesthetics are less critical.

The selection of shielding gas should be based on the specific goals of the laser process, whether prioritizing surface smoothness, oxidation resistance or cost efficiency. While gas type plays a central role in process outcomes, it is not the only determining factor. The following chapter explores how gas flow parameters, such as pressure and distance, influence surface quality in laser processes.

3 Parameters related to shielding gas

Gas parameters such as flow rate, nozzle distance, gas type, and shielding method influence laser surface processes significantly. These parameters can have an impact on surface roughness, oxidation levels, heat dissipation and material removal rates. The following sections discuss their effects on laser surface processes.

3.1 Effects of gas flow rate and pressure

Ali et al., (2023) found in a study that excessively high gas flow rates can lead to turbulence in the melt pool while laser polishing. The turbulence was found to increase microstructural defects and reduce uniformity. concluded on their study on laser polishing of titanium alloys that flow rates exceeding 20L/min caused surface instability and inconsistent roughness values (Ali et al., 2023)

Temmler et al., (2020) conducted an in-depth study on laser micro-polishing by using argon and nitrogen as a shielding gas. Gas flow rates between 10-40 l/min were tested, showing minimal change on the overall surface roughness. Higher gas flow rates were found to lead to turbulence and it induced surface irregularities. Short nozzle distances combined with high gas flow rates introduced micro-waviness and streaks due to capillary waves induced by turbulent gas flow. Local gas shielding (nozzle-based) was found to be a feasible approach for laser micro-polishing, allowing effective shielding for large areas. Chamber gas shielding provided the most stable oxidation prevention, but local shielding using a nozzle yielded comparable results under controlled conditions (Temmler et al., 2020). In laser engraving of CR12MoV steel, argon shielding (5 L/min) preserved micro-hardness and prevented excessive grain coarsening. Oxygen-assisted engraving (5 L/min) led to a loss of carbon, which reduced hardness in the remelted layer (Xing et al., 2021a)

Giorleo et al., (2015) investigated the effect of gas pressure on laser polishing of Titanium Grade 2 using nitrogen as the assist gas. The angle of the shielding gas was 45 degrees from the workpiece. They found that low gas pressures (0-5 bar) provided more homogenous surface roughness, while avoiding molten droplets or oxidation artifacts. High nitrogen gas pressures introduced surface instabilities and inconsistent roughness results. Figure 3 displays the impact of varying gas flow rates on surface quality, illustrating the sensitivity of the process. (Giorleo et al., 2015)

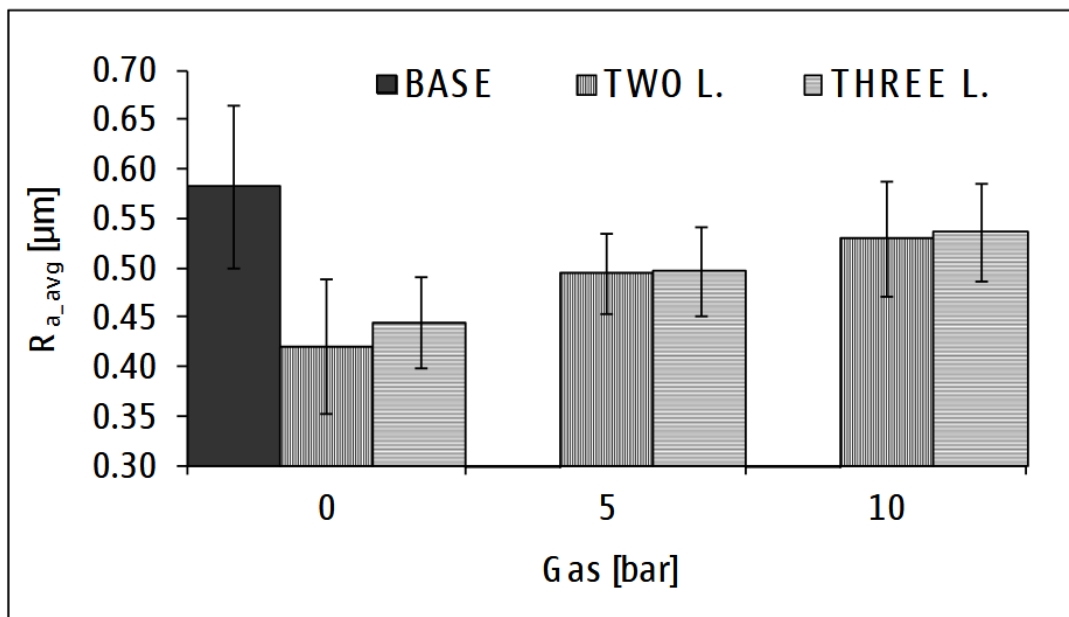


Figure 3. medium average surface roughness with different nitrogen gas pressures, by comparing two line- and three line laser filling paths. (Giorleo et al., 2015)

In the experimental results shown in figure 3, it is evident that raising the pressure of shielding gas had a negative effect on the surface roughness. One potential explanation for this is the angle of the shielding gas, which in this case was set to 45 degrees. The gas angle may have caused partial shielding leading to uneven protection. Also, the shear forces of the angled gas might have affected the geometry of the melt pool negatively, leading to micro-waviness. These findings suggest that a perpendicular gas angle typically provides better shielding and minimizes turbulence, since with every other study, a lower surface roughness was achieved when using shielding gas perpendicularly. With a larger angle, shear forces and flow instability can disturb the melt pool, especially in precise laser polishing.

The distance of the nozzle also plays a crucial role in oxidation prevention and surface roughness. In titanium laser polishing, a 15 mm nozzle distance provided the most stable flow, whereas shorter distances caused turbulence, leading to surface irregularities. The gas pressure of 5 l/min was optimal, whereas higher pressures disrupted melt pool stability in nozzle gas shielding (Xu et al., 2023). For precision laser polishing applications, distances beyond 20 mm were found to reduce the effectiveness of the shielding gas, leading to increased oxidation and inconsistent melting patterns (Ali et al., 2023)

3.2 Summary: effects of gas flow parameters on laser surface processing

Table 2 illustrates optimal gas parameters, providing practical guidelines for process optimisation.

Table 2. Influence of shielding gas parameters on surface quality and process stability in laser surface processing. Compiled from (Giorleo et al., 2015; Temmler et al., 2020; Wang et al., 2023; Xing et al., 2021b; Xu et al., 2023)

Parameter	Optimal range	Effects if too low	Effects if too high	Notes / observations	Reference
Flow rate	5-15 l/min (typical)	Inadequate shielding, oxidation, higher surface roughness.	Turbulence, ripple defects, shear stress, melt pool instability	Optimal range depends on gas type and shielding method (nozzle vs. chamber)	(Ali et al., 2023; Giorleo et al., 2015; Temmler et al., 2020)
Flow rate (argon)	5-10 l/min (nozzle)	Surface roughness due to oxidation	Ripple formation at melt pool surface		(Ali et al., 2023; Giorleo et al., 2015; Temmler et al., 2020; Xing et al., 2021a)
Flow rate (nitrogen)	10-20 l/min	Oxidation on reactive surfaces	Increased surface waviness and irregularities	Higher flow caused capillary waves and micro-waviness	(Ali et al., 2023; Giorleo et al., 2015; Temmler et al., 2020; Xing et al., 2021a)
Gas pressure	0-5 bar (typical)	Poor coverage, oxidation artifacts	Shear forces, molten droplet formation	Misalignment of angle can reduce melt pool stability and cause asymmetry	(Giorleo et al., 2015)
Nozzle distance	4-15 mm	Turbulence if too close (<2 mm)	Oxidation if too far away (>20 mm)	Short distances with high flow rates caused micro waviness. 4 mm was optimal in laser micro-polishing	(Ali et al., 2023; Xu et al., 2023)

Table 2. Influence of shielding gas parameters on surface quality and process stability in laser surface processing. Compiled from (Giorleo et al., 2015; Temmler et al., 2020; Wang et al., 2023; Xing et al., 2021b; Xu et al., 2023)

As it can be seen from Table 2, Parameters such as flow rate and pressure influence the outcome of the processes significantly, often as much as the gas type itself. Proper control of

these parameters is essential to ensure effective shielding, consistent surface quality and stable melt pool behavior.

Optimal flow rates for inert gases like argon and nitrogen typically range between 5-15 l/min, depending on the shielding type (chamber or nozzle). Flow rates below this range might result in inadequate shielding, allowing oxidation and increasing surface roughness. In contrast, excessive flow rates can lead to turbulence and shear stresses. These forces introduce surface defects such as ripples or micro-waviness, particularly when using nozzle shielding. Gas pressure also plays a crucial role. Pressures between 0-5 bar are generally considered optimal. Higher pressures can cause molten droplet formation and surface instability due to uneven shear forces, especially when combined with short nozzle distances.

In summary, even the best shielding gas can yield suboptimal results if flow parameters are not tuned properly. Stable gas flow, minimizing turbulence and ensuring full coverage of the processing surface are essential in optimizing the process.

4 Shielding gas delivery method in surface processes

The way that the shielding gas is delivered in laser surface processing is critical in determining the quality of the final surface. Beyond the gas type and the flow parameters, the geometry of gas introduction, and the overall shielding strategy has an impact on oxidation levels, surface roughness, and heat distribution.

4.1 Chamber shielding vs. nozzle shielding

Gas shielding can be introduced either through local shielding using a nozzle or through global shielding by using a chamber and enclosing the workpiece in that. Each method has distinct advantages depending on the application. In nozzle shielding (local shielding) the shielding gas is delivered locally through a nozzle, directed at the laser-material interaction zone. The nozzle is typically mounted near the laser head and can be angled or positioned to follow the laser scan. In chamber shielding (global shielding) the entire part is placed inside a sealed chamber filled with shielding gas.

In the laser polishing process of austenitic stainless steel (304), argon shielding at different flow rates was analyzed by Xu et al., (2023). Figure 4 illustrates nozzle shielding and chamber shielding setups, providing a visual overview of their structural and functional differences.

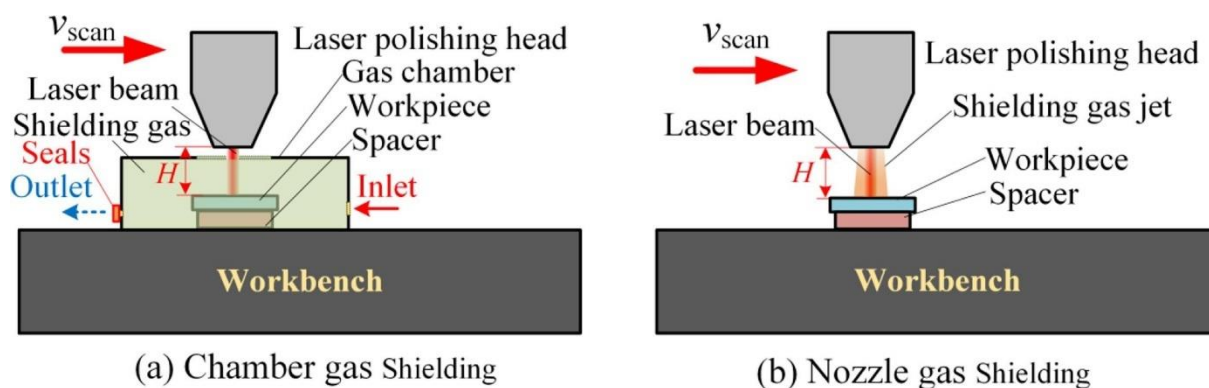


Figure 4. Chamber gas shielding and nozzle gas shielding (Xu et al., 2023)

The optimal flow rate for nozzle shielding (Figure 4b) was found to be 10 l/min, achieving a surface roughness (Ra) of 0.5 μm . Lower flow rates (1-5 l/min) increased value of roughness ($>0.6 \mu\text{m}$) because of inadequate shielding. In chamber shielding (figure 4. a), higher flow

rates produced a smoother surface. With flow rates of 15-20 l/min the surface roughness (Ra) was about 0.5 μm (Xu et al., 2023).

Chamber gas shielding and nozzle gas shielding were found to be similar in performances up to gas flow rates of 10 l/min. The benefits of chamber gas cleaning are not improved with higher gas flow rates, as seen in figure 5.

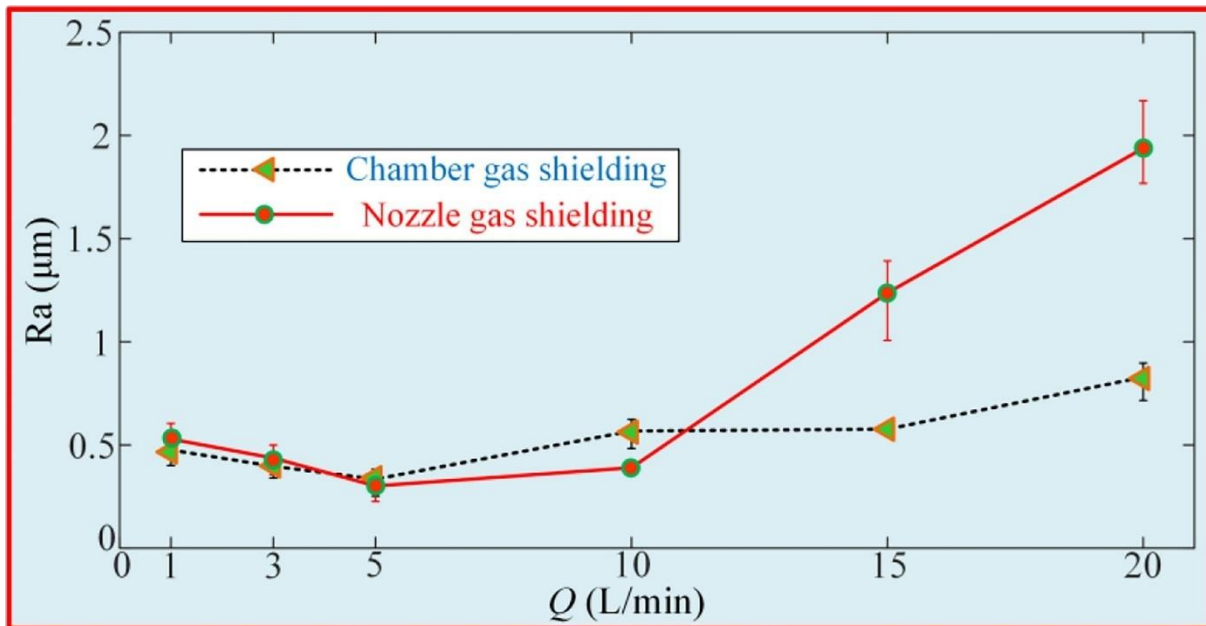


Figure 5. Gas flow rate (Q) effects on surface roughness after laser polishing in nozzle gas cleaning and chamber gas cleaning with argon. (Xu et al., 2023)

The shielding effect of the shielding gas steadily rose as the flow rate increased from 1 l/min to 5 l/min, which resulted in a gradual decrease of the surface roughness (Ra) of the workpiece. The minimum surface roughness that was achieved in chamber gas shielding was 0.4 μm and with nozzle gas shielding the minimum roughness was 0.3 μm . Xu et al. (2023) found that both chamber and nozzle shielding achieved surface roughness below 0.5 μm when properly tuned. However, nozzle shielding introduced ripple defects at higher gas flow rates due to increased shear stress, while chamber shielding remained stable. This highlights that while both methods can be effective, the choice depends on the application and tolerance for surface defects. (Xu et al., 2023)

At higher flow rates (15-20 L/min), nozzle shielding introduced arc-shaped surface ripples, likely caused by shear stress induced on the melt pool by the gas nozzle. Chamber shielding did not exhibit these artifacts, making it more stable for maintaining surface integrity under

turbulent conditions. Temmler et al. (2020) confirmed that chamber shielding provided the most stable oxidation prevention, which was found to be particularly useful for high-precision micro-polishing. However, local nozzle shielding is more flexible for larger components and industrial-scale setups, provided that flow parameters and nozzle distances are optimized (Temmler et al., 2020).

Local nozzle shielding is often preferred due to its flexibility, especially for large or continuous components. Dadbakhsh et al. (2010) demonstrated that local shielding using argon was sufficient to prevent oxidation in laser polishing of Inconel 718. However the effectiveness of this approach depends heavily on precise control of the parameters, which makes the possibility of failure greater. (Dadbakhsh et al., 2010).

Chamber shielding is less practical for large parts, but it offers the advantage of a completely controlled atmosphere. It is especially beneficial for materials which are extremely sensitive to oxidation or when ultra-fine surface finishes are needed without risk of turbulence-induced defects. However, making a controlled atmosphere is more time-consuming since the chamber must be filled with gas and oxygen must be purged from the chamber before processing.

Table 3 compares the performance of nozzle shielding versus chamber shielding, outlining their respective strengths and limitations.

Table 3. Comparison of Nozzle Shielding and Chamber Shielding. Compiled from (Dadbakhsh et al., 2010; Temmler et al., 2020; Xu et al., 2023)

	Nozzle shielding	Chamber shielding
Coverage area	Local (focused on melt zone)	Entire part uniformly surrounded
Setup Time	Fast	Slower (Chamber must be filled and sealed)
Gas Efficiency	Higher (less gas used)	Lower (larger volume of gas needed)
Cost	Lower	Higher (especially for larger parts)
Flexibility	High (good for large or complex parts)	Limited to small/medium -size parts
Oxidation Protection	Good if parameters are optimized	Excellent and consistent
Risk of Turbulence	Higher (depends on nozzle distance/angle)	Minimal if chamber is sealed properly
Ideal For	Industrial-scale or mobile setups	Lab research, micro-polishing, oxidation sensitive materials.

As it can be concluded from table 3, nozzle shielding is often preferred due to its flexibility and ease of implementation on larger or complex-shaped components. It allows continuous processing without the need for sealed environments. However, for ultra-precise polishing or oxidation-sensitive materials, chamber shielding provides the most stable and uniform gas coverage. The trade-off between cost, complexity, and quality should guide the selection of shielding method (Dadbakhsh et al., 2010).

4.2 Effect of nozzle distance and angle

The distance between the gas nozzle and the surface of the workpiece has a direct impact on the shielding performance in laser polishing. Figure 6 illustrates the experimental setup used by Temmler et al. (2020), showing the configuration of the inert gas nozzle. A coaxial gas nozzle was used, mounted beneath a focusing lens and aligned on an optical rail. This setup was equipped with a high-speed mechanical axis for moving the laser optics while the workpiece remained stationary.

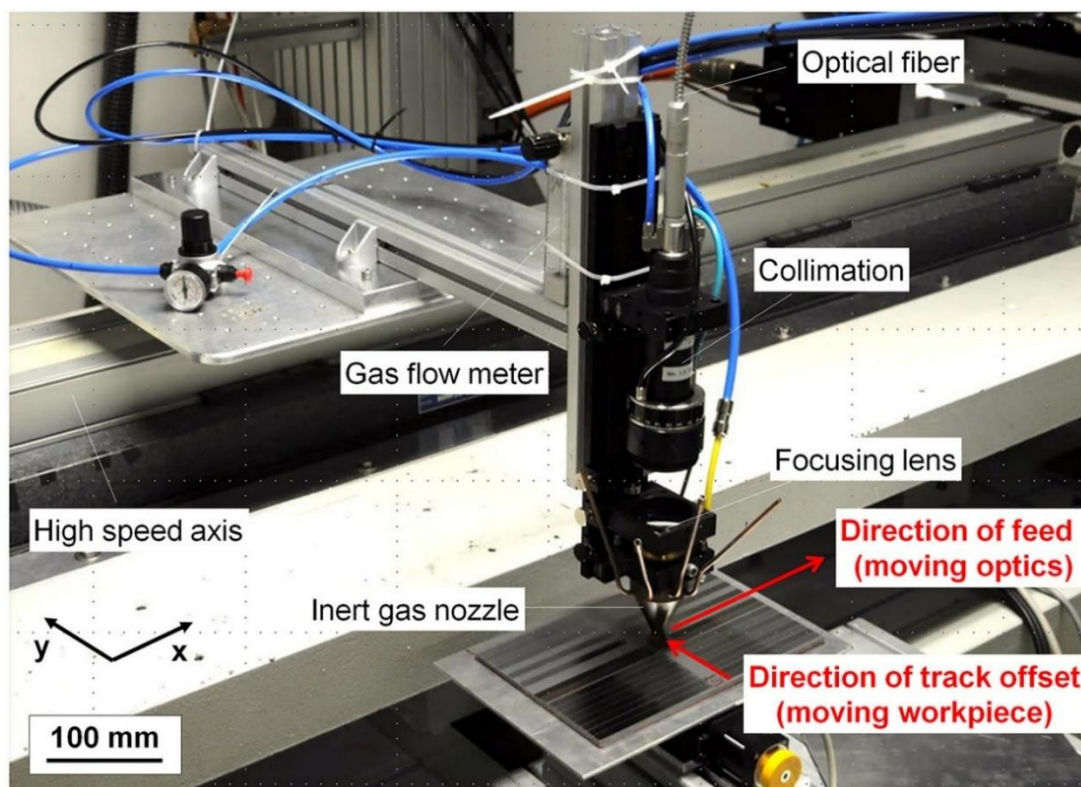


Figure 6. experimental set-up for laser processing with nozzle gas shielding (Temmler et al., 2020)

Temmler et al., (2020) found that short nozzle distances (1-2 mm) combined with high flow gas flow rates (40 l/h) introduced micro-waviness on the surface resulting from turbulence and capillary waves forming in the surface melt pool (figure 7 a). When increasing the nozzle

distance to 4 mm and lowering the flow rates (10 l/h), the polishing results were more uniform as shown in figure 7 b (Temmler et al., 2020).

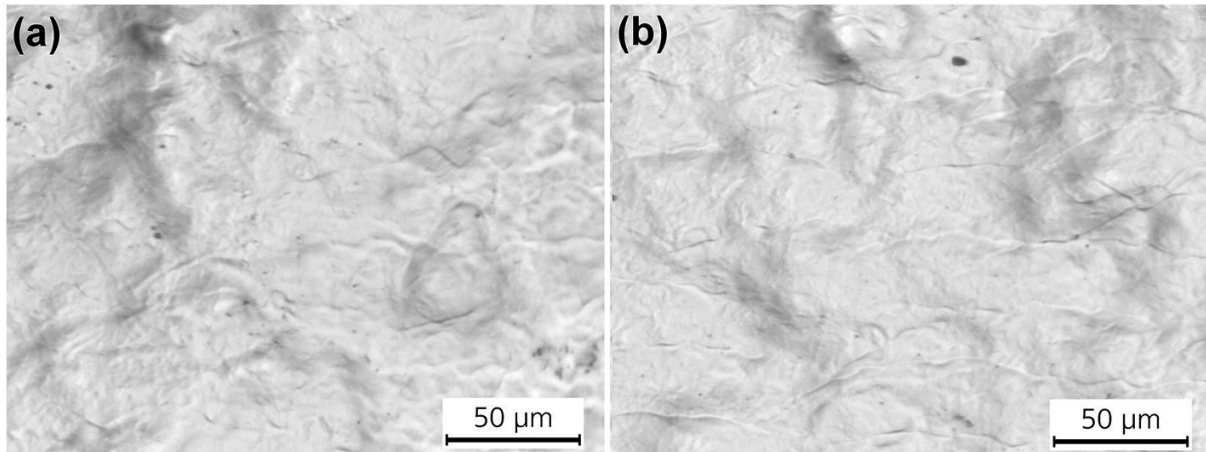


Figure 7. Laser polished surface of stainless steel 410 with (a) nozzle distance of 1 mm and flow rate 40 l/h, and (b) nozzle distance of 4mm and flow rate of 10 l/h

Ali et al., (2023) observed that in laser polishing of Ti-6Al-4V, a 12 mm nozzle distance combined with 15 L/min flow rate provided stable shielding, reducing roughness by over 85% (Ali et al., 2023). In another study, Young et al. (2018) noted that keeping nozzle distance at around 5mm when laser polishing yielded an optimal surface finish of 0.4 µm with argon shielding. (Yung et al., 2018)

Gas angle is also a factor, though it is less studied. Poorly angled nozzles can result in partial coverage or uneven shear forces, both of which negatively affect the melt pool stability and surface finish. Giorleo et al. (2015) used a 45-degree angle of gas flow with respect to the workpiece. In the experiment, the best surface roughness results were achieved with lower gas pressures (0-5 bar). With high gas pressures (10 bar) the gas introduced surface instabilities and molten droplets, which might be an effect of the gas flow angle (Giorleo et al., 2015).

Stable gas flow is also essential to ensure even cooling and oxidation prevention. In a study on laser polishing of titanium alloys, Ermergen et al. (2023) showed that when the flow of shielding gas was disturbed during the polishing process, the result was a visibly non-uniform surface with discolored oxidation zones and reduced hardness. In contrast, a stable and directed gas flow maintained consistent results (Ermergen et al., 2023). Xu et al., (2023) used mathematical modeling to demonstrate how jet-induced shear stress from the gas flow

interacts with the melt pool. The results showed that increased gas pressure or a deviation in the angle can distort the molten surface, which resulted in the formation of ridges and a reduction in uniformity (Xu et al., 2023). Lu et al. (2024) confirmed this by emphasizing that unstable gas flow leads to defects like ripple formation and uneven hardness. (Lu et al., 2024)

4.3 Gas direction relation to gas type

The effectiveness of shielding gas in laser surface processing does not only depend on its chemical properties, but also on how it is introduced on the workpiece. Improper gas delivery, such as turbulence resulting from a poorly angled nozzle or excessive flow rates, can neutralize the benefits of inert gases like argon or nitrogen. Chamber shielding offers the highest protection but is limited by practical constraints. Nozzle shielding is more adaptable, but it requires careful optimization of angles, nozzle distance and flow rate to avoid surface roughness. Selecting the right gas direction method is therefore essential for achieving optimal results. (Ermergen et al., 2023; Temmler et al., 2020; Xu et al., 2023)

5 Conclusions

This thesis analysed how shielding gas type, gas parameters, and gas delivery methods affect the outcomes of laser surface processing applications such as polishing, cleaning, and engraving. The main goal was to understand how shielding gas selection and optimisation influence surface quality, oxidation resistance and microstructural changes, drawing insights from literature and comparative studies.

The review shows that the choice of shielding gas is essential, but its performance depends heavily on process parameters. Inert gases like argon and nitrogen provide the best oxidation prevention and surface smoothness. Reactive gases such as oxygen and carbon dioxide increase material removal rates, but risk introducing surface defects. However, even the best shielding gas can yield poor results if flow rate, pressure, nozzle distance, or gas angle are not properly tuned. For example, excessive gas flow or poor nozzle alignment can cause turbulence and shear stress, leading to ripples or inconsistent shielding. Chamber shielding generally provides the most uniform protection but is slower and less practical for large parts compared to nozzle shielding.

Overall, the thesis highlights that the combined optimisation of gas type, delivery method, and process parameters is critical for achieving high-quality laser surface outcomes. These findings can help guide future process improvements and more efficient industrial applications.

6 Further studies

While this thesis provides a comprehensive review of the effects of shielding gases on laser surface processing, areas remain open for future research.

More experimental work is needed to validate the combined influence of gas type, flow parameters, and delivery methods under industrial conditions, especially for complex part geometries and larger surface areas. Current literature often focuses on controlled laboratory settings, which may not fully capture the challenges faced in practical applications. Future studies could also explore the use of mixed gas environments, such as combining argon and nitrogen for a lower cost alternative. Investigating how these gas mixtures affect microstructure and surface properties would help expand the current understanding beyond single-gas systems.

Developing real-time monitoring and control systems that adjust gas flow rates, pressures, and nozzle positions dynamically during laser surface processing could improve process consistency, reduce defects, and optimise gas consumption. Also, numerical modelling and simulation studies could provide insights into gas flow dynamics and melt pool behaviour under different shielding conditions, complementing experimental findings.

Addressing these areas in future research would help translate the theoretical and literature-based insights of this thesis into industrially applicable laser surface processing solutions.

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