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Development of a CO_2 snow jet blasting strategy for controlling the thermal influence on the substrate

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Abstract
The utilization of CO_2 snow jet blasting in precision engineering applications has gained significant interest due to gentle substrate treatment and effective cleaning capabilities. This study investigates the thermal influence of CO_2 snow jet blasting on the substrate and strategies to control it. CO_2 snow jet blasting contaminate removal works through a combination of mechanical impact and thermal shock. As the pressurized liquid CO_2 exits the nozzle, it forms CO_2 snow particles. These particles are further accelerated by a compressed air jacket. The CO_2 snow particles impact the surface at high velocities v_s, dislodging contaminants. The rapid temperature reduction $\Delta\vartheta$ induces thermal stress σ_T between the contaminants and the substrate, assisting in contaminant removal. This also induces thermal gradients $\nabla\vartheta$ and thermal stress σ_T within the substrate. Extended exposure durations t_e result in more substantial temperature reductions $\Delta\vartheta$. Cleaning experiments were conducted while simultaneously tracking the temperature ϑ in relevant areas. Different cleaning strategies and process parameters were varied. The findings enhance the understanding of thermal behaviors in CO_2 snow jet blasting and provide insights for improving precision cleaning processes in advanced manufacturing.
Keywords: precision cleaning, CO_2 snow jet blasting, thermal behaviour, sustainable-cleaning

1. Introduction

CO_2 snow jet blasting has already established itself as a gentle and precise cleaning method in specific industries [1]. As a process variant of blasting technologies that utilise solid CO_2 as the abrasive medium, it exhibits many of the same properties as dry-ice blasting that are inherent to the medium. The primary benefit of solid CO_2 is its ability to leave surfaces dry and residue-free. Under atmospheric pressure p_A the solid CO_2 sublimates, meaning a direct transition between the solid and gaseous states, leaving behind no residue on the substrate. The main procedural difference between dry-ice and CO_2 snow jet blasting lies in the supply of the blasting medium. While dry ice blasting accelerates pre formed pellets of solid CO_2, CO_2 snow jet blasting uses liquid CO_2 as the source. When exiting the nozzle at high pressure p and ambient temperature ϑ_A the liquid CO_2 experiences a sudden relaxation with a pressure difference Δp, which coincides with a rapid cooling due to the Joule-Thomson effect, forming a mixture of solid CO_2 particles and gaseous CO_2 [2]. This mixture is typically further accelerated by a pressurized air stream to increase the abrasiveness and focus the jet. CO_2 snow jet blasting relies on three main mechanisms for contaminant removal: the mechanical effect through the impact of solid CO_2 particles, the sublimation effect due to the rapid expansion of sublimating CO_2 and the thermal effect [3]. The thermal effect occurs due to the temperature differences between the solid CO_2 at ϑ_{CO2} = -78.5 °C and the substrate and contamination, typically at ambient temperature ϑ_A. The sudden temperature reduction $\Delta\vartheta$ induced by the solid CO_2 particles impact leads to thermal stress σ_T between the contaminants and the substrate, assisting in the removal of contaminants [4]. While in most applications an increase in cleaning capabilities through thermal shock is beneficial, it can also be detrimental when cleaning parts bonded with adhesives or solder joints, both often found on PCBs or other thermal sensitive substrates [5]. This paper shows the initial findings of experiments using CO_2 snow jet blasting to clean a uniformly applied film of lubricating oil from a 316L stainless steel surface. The influence of varying process parameters and pathing strategies on the observed cleanliness and temperature ϑ are presented and discussed based on the experimental data.

2. Methodology

A multitude of machines and devices were used for cleaning, pathing, measurement and analysis of the samples. A six-axis robotic arm was used for consistent pathing, temperature data was collected by thermocouples, cleanliness data by fluorescence measurements. The design of experiments and data analysis were carried out in Minitab.

2.1 Devices and Setup

A single two-component concentric nozzle was used for the CO_2 snow blasting with the media supply being realized by the Jetworker system of the company ACP SYSTEMS AG, Zimmern ob Rottweil, Germany. This nozzle was mounted to the end-effector of a six axis robot KR 10 R900-2 of the company KUKA AG, Augsburg, Germany for positioning along the defined paths. The Temperature measurements were taken via thermocouples of the type K and recorded via the program LABVIEW of the company, NATIONAL INSTRUMENTS, Austin, United States. It is important to note, that the thermocouples were attached to the underside of the substrate, made of 316L stainless steel with measurements of 200 mm x 100 mm x 2 mm, as to not impede cleaning effects on the surface. As such, recorded temperatures ϑ_R are higher than surface temperatures ϑ_S but still deliver insights into process driven thermal control. The resulting cleanliness of the samples was measured using the SITA CleanoSpector of the company

SITA Messtechnik GmbH, Dresden, Germany which detects residual filmic contaminations by fluorescence measurements.

2.2 Design of experiments

The traversing speed v_f, the number of repetitions r as well as the pathing were varied to influence temperature ϑ_R and cleanliness results. The traversing speed v_f was varied in three even steps in a range of $0.04 \text{ m/s} \leq v_f \leq 0.12 \text{ m/s}$, the pathing was carried out either once or twice and the paths varied between a meander from one end to the other and a rectangular spiral from the inside out, shown in figure 1. It is important to note, that the traversing speed v_f was doubled in experiments where the path was repeated as to achieve the same exposure durations t_e. This resulted in a full factorial design encompassing 12 runs, which were repeated once. This process resulted in a total of 24 runs. Other relevant process parameters were held constant. The path spacing was set to a = 3.5 mm, the capillary diameter to $d_k = 0.4$ mm, the air pressure to p = 0.7 MPa, the stand off distance to s = 25 mm and the incidence angle to α = 90°.

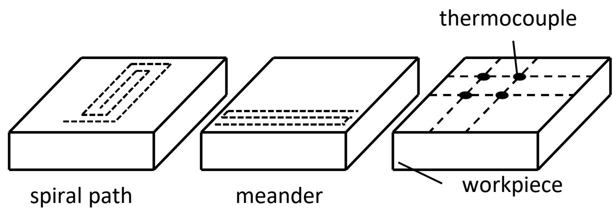

Figure 1 experimental setup and procedure

4. Results and discussion

The initial experimental analysis shows clear trends considering the impact of the varying settings on cleanliness and temperature. For the analysis, the minimum recorded temperatures of each thermocouple ϑ_{min}, during each run with the given setting, and the rest fluorescence f_r, recorded at four points above the thermocouples, were averaged per parameter step. For reference, when measuring the samples rest fluorescence f_r after manual Isopropanol cleaning, it averaged to $f_r = 30$ RFU, the initial contaminated surfaces showed rest fluorescence values $f_r \approx 2000$ RFU. Lower residual fluorescence values f_r indicate a cleaner surface. Figure 2 shows the relations between traversing speed v_f and rest fluorescence f_r as wells as temperature ϑ_{min}. Lower temperatures ϑ_{min} and rest fluorescence values f_r coincide with lower traversal speeds v_f. This is to be expected due to an increased exposure duration t_e.

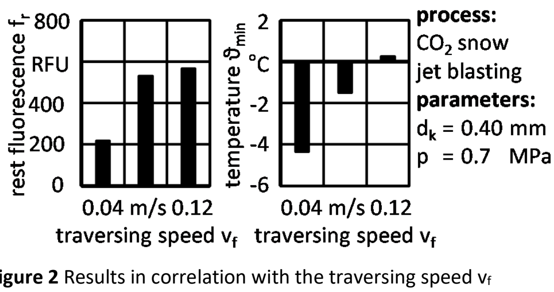

Figure 2 Results in correlation with the traversing speed v_f

Figure 3 demonstrates the correlation between the number of repetitions, the rest fluorescence f_r as wells as the temperature ϑ_{min}. An increased cleanliness and lower temperatures ϑ_{min} are observed when running multiple repetitions of the pathing. While running multiple repetitions the temperature development showed two lowpoints when the incidence area was directly above the thermocouples with a climb in temperature in between, yet the averaged recorded temperatures ϑ_{min} are lower than for a single run.

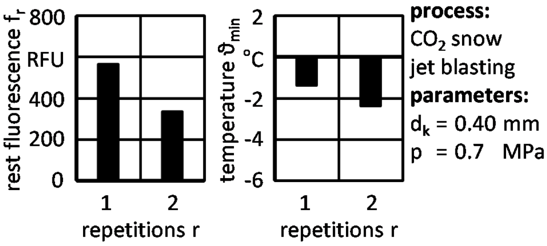

Figure 3 Results in correlation with the repetitions r

The influence of the pathing on rest fluorescence f_r and temperature ϑ_{min} are shown in figure 4. Using spiral pathing, on average higher temperatures ϑ_{min} and lower rest fluorescence values f_r were recorded. The temperature differences $\Delta\vartheta$ is caused by differing thermal propagation based on the pathing while the higher cleanliness is assumed to be due to an increase in the thermal effect as well as advantageous contaminant removal mechanisms.

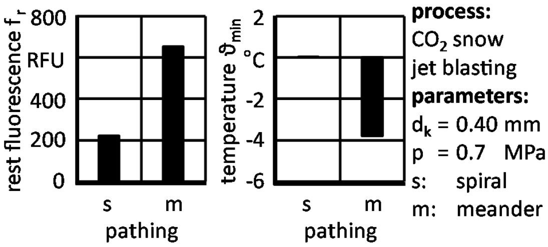

Figure 4 Results in correlation with the pathing

5. Conclusion

The paper provides an approach on parameters and strategies to be employed in the context of CO_2 snow jet blasting, with a view to achieving the desired level of cleanliness, as well as the control of substrate temperature ϑ. Especially the spiral pathing showed improved cleanliness results while decreasing the substrate temperature ϑ. It is to be noted that improved cleanliness results over isopropanol cleaning were only achieved with traversing speed $v_f = 0.04$ m/s, repetitions r = 2 and spiral pathing. While the experiments were conducted on a homogeneous material, this is often not the case in industrial applications. Despite this influencing the thermal propagation, the parameters and methods should still hold their effect. Some parts such as printed circuit boards (PCBs) use adhesives for surface level bonding and solder joints, which are sensitive to thermal shock. As such, for the application of CO_2 snow jet blasting, it is important to reduce the thermal influence on the substrate to not release bonded parts or damage solder joints. Further investigations into the direct effect of CO_2 snow jet blasting on PCBs should be carried out.

References

[1] Rögner F, Pfeilschifter M, 2021 Markt- und Trendanalyse in der industriellen Teilereinigung. Geschäftsbereich Reinigung bei Fraunhofer.

[2] Kretzschmar M, 2017 CO2-Schneeentstehung und deren Wirkung auf die Effekte beim CO2-Schneestrahlen. Berlin, Fraunhofer Verlag.

[3] Uhlmann E, Hollan R, 2015 Blasting with Solid Carbon Dioxide – Investigation of Thermal and Mechanical Removal Mechanisms. Procedia CIRP 26 (2015) 544 – 547.

[4] Krieg M, 2008 Analyse der Effekte beim Trockeneisstrahlen. Berlin, Fraunhofer Verlag.

[5] Zhou Z, Chen J, Yu C, Wang Y, Zhang Y, 2023 Failure Analysis of Printed Circuit Board Solder Joint under Thermal Shock *Coatings* 13 572.