A Laser Assisted Dry Ice Blasting Approach for Surface Cleaning LCE2006

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Abstract

Surface cleaning processes are needed in different life cycle phases of technical products. They are important elements in manufacturing and in maintenance during usage as well as in recycling and remanufacturing. To meet the increasing requirements in product durability and functionality, the usage of compound materials and functional coatings becomes over more important. In this regard surface cleaning is an essential processes to ensure the reliability of pre-treatment and coating process. While product data are well known or can easily be determined during manufacturing and maintenance, this is not the case at the end of life cycle. To manage the lacking knowledge of the contaminants as well as to deal with the removal of worn coatings on products, highly flexible cleaning processes are needed.

Usually the cleaning processes are based on conventional methods. Dry ice blasting and laser processing are two environmentally friendly alternatives with different advantages. Dry ice blasting can be used for delamination, cleaning and pre-treatment while laser processing makes a defined removal of coatings or contaminants and a surface treatment of the recycling part possible. With regard to highly adhering or hard contaminants and protective or functional coatings they have technological and economical limitations. Furthermore sensitive substrate materials may be damaged partially. The hybrid combination of both technologies offers different strategies for machining: The laser can be applied either as an energy source to intensify the thermal mechanism of dry ice blasting or as a final cleaning process. With respect to the material removal rate the hybrid machine concept shows a significant improvement compared to the stand-alone-technologies.

Keywords

Dry ice blasting, laser processing, hybrid machine tool concept, disassembly, reuse, remanufacturing, life cycle engineering, maintenance, recycling

1 INTRODUCTION

In case of high value raw materials or high expenses for manufacturing the recycling of products is reasonable. This implies as well used products as faulty coatings of products within the manufacturing process. Recycling saves money and resources. Therefore it is economically and ecologically favourable. Usually for recycling a cleaning or also a de-coating process is necessary using mechanical, chemical or aqueous methods. But these conventional technologies are often time- and energy-consuming. Furthermore they involve high costs for waste disposal and personnel while offering only low flexibility [1].

Dry ice blasting is a blasting process, that uses pellets of solid carbon dioxide as blasting media. The so called dry ice pellets are fed out of a storage element into a compressed air stream. This stream accelerates the pellets through a blasting nozzle onto the workpiece. The laser processing may be applied either focused or unfocused. A conventional focused laser (the specimen surface to be cleaned is aligned in the focus level) may serve as a final cleaning step while a de-focused laser increases the thermal effect of the dry ice blasting by heating the surface of the specimen.

In opposition to conventional technologies dry ice blasting and laser processing generate no additional liquid or solid waste apart from the removed contaminants or coating [2]. With regard to special cases of applications and to the economical point of view both technologies have their respective limitations.

The objective of Hybrid Dry Ice Blasting-Laser Processing is to increase the area-related cleaning and de-coating ratio. The combination of both technologies will expand their economical and technological limitations. An easy replicable substrate-varnish combination has been chosen from the variety of materials, coatings and contaminants. With this standard substrate-varnish combination the process parameters of each stand-alone-technology have been optimized. Thereafter the results of these investigations have been compared with the results of the hybrid experiments.

2 APPLIED CLEANING TECHNOLOGIES

2.1 Dry Ice Blasting

Dry ice blasting is based on a mechanical effect caused by the impact of the dry ice pellets, a thermal mechanism due to a local cooling down effect at the impact point [3] and an expansion because of the partial sublimation of the pellet. Due to this, elasticity is lost and the coating embrittles and shrinks. Different thermal expansion coefficients of substrate and coating produce cracks in the coating. The kinetic energy of the particles and the air stream contribute to the removal. The sublimation of the dry ice leads to a sudden increased volume by the factor 700 that supports the process [4]. When the adhesive energy is exceeded by this combined thermo-mechanical effect the coating chips off [2].

The solid carbon dioxide is used as one-way blasting medium. It is transformed of liquid carbon dioxide, that is stored either in low pressure tanks at a temperature of –20°C with a pressure of 20 bar or high pressure tanks at +20°C at 57 bar [5]. When it is expanded quickly to atmospheric pressure, it is cooled down to -78.5°C because of the Joule-Thomson-effect and solid carbon dioxide snow is generated [6, 7]. A hydraulic stamp presses the carbon dioxide snow through conical holes of a mould and finally forms the cylindrical dry ice pellets. The pellet parameters (density, hardness, shape) are influenced by the conditions during their production (e.g. degree of compaction).

A fundamental advantage of dry ice blasting is that there are no residues left due to the sublimation of the dry ice. While other cleaning processes require complex processing or increase disposal costs no media remains in the structure of the workpiece (e.g. boreholes and cavities) [2]. No special cleaning equipment is needed for the exhausted air due to the non-toxic blasting medium carbon dioxide. Except the removed coating-particles might have to be filtered off. Because of the non corrosive and non abrasive behaviour no post-treatment is needed for the workpiece. Dry ice blasting allows a flexible soft delamination and cleaning even of sensitive or structured surfaces. Contaminants and protective films (e.g. paint of metal components) can be removed by dry ice blasting. Highly adhering or hard contaminants and protective or functional coatings are difficult to remove. A complete removal of rust by dry ice blasting is e.g. impossible.

Despite the advantages of dry ice blasting as a highly flexible cleaning technology there are also disadvantages. The solid carbon dioxide used as blasting media sublimates and has to be sucked off with regard to maximum allowed work place concentration for gaseous carbon dioxide. These limits depend up on the country (e.g. Great Britain STEL 15000 ppm, LTEL 5000 ppm; Germany MAK 5000 ppm [5]). The released carbon dioxide is a chemical by-product of different chemical synthesis processes in the chemical industry (e.g. ammoniac synthesis according to the Haber-Bosch process as well as hydrogen and ethanol synthesis) [6]. Therefore it does not contribute to the greenhouse effect.

Further more the operator has to be aware of the danger due to the cold temperatures and has to carry out special safety instructions. Another disadvantage is the high sound pressure level of up to 125 dB(A) due to the high blasting pressure. To maximize the mechanical impact of the pellets, the velocity of the air stream in the accelerating blasting nozzle is increased by rising the blasting pressure. The operator has to wear adequate hearing protection to carry out further safety instructions while the process should be hermetically sealed.

2.2 Laser Processing

Laser processing is a field of increasing significance in recent years. The laser beam is focussed by a lens concentrating the laser energy in a focus of a few microns and determining the cauterisation of the laser beam, e.g. the focal distance. Usually a scanner system consisting of two swivelling mirrors allow the machining of a level aligned in the focal distance (focused). To machine a 3D-shape an additional positioning system either of the specimen or of the scanner system is needed. By this focused laser application surfaces can be cleaned, structured or modified flexibly and precisely by laser processing due to specific parameters. The controlled application of energy allows a melting or sublimating of the surface material, depending on the composition and thickness of the contaminant or coating as well as on the parameters of the laser process. Further fields of application are the removal of paint from metal components (e.g. exchange engines) [8], the removal of scale from welding seams [9] as well as the cleaning of railroads, memorials and pylons.

Cleaning and de-coating by laser processing offers significant advantages. It combines contact- and force-free processing of high precision with low thermal and mechanical influence that can be applied to sensitive surfaces. Offering a selective cleaning the depth of removal of consistent material is easy to control. Therefore a high degree of automation, especially an online-control is possible. The removal of thick contaminants and coatings is the economical, sometimes even technological limitations of the application. The more abrasive the parameters of laser processing are the higher is the risk of damaging the surface of the substrate below an inconsistent coating or contaminant.

For laser processing also special safety instructions are necessary. According to the type, wavelength and power of the laser the process needs an appropriate shielding. Further more the staff has to wear an eye protection and carry out specific safety instructions also with respect to the danger due to the high voltage of the laser source.

2.3 Hybrid Dry Ice Blasting-Laser Processing

Worn hard coatings like thermal sprayed thermal barrier coatings (TBC) of gas turbine parts could hardly be removed by dry ice blasting due to the low hardness of the pellets. Because of high raw material values and expenses for the manufacturing process of gas turbine blades the maintenance and recycling of these parts is of high interest. Though this method [10] is economic as well as ecologic favourable compared to conventional removal methods the dry ice consumption is high. The hybrid concept offers a reasonable reduction of this consumption.

The cleaning of complex three dimensional moulds in the automotive industry might become another field of application. Due to the sensitive materials dry ice blasting is limited to a specific blasting pressure.

The combination of both technologies offers different strategies of machining. According to the relative position of the laser and the specimen the laser can be applied focused and unfocused. Depending on the laser and the dry ice blasting device both technologies can be applied in the same focal point or in different focal points. Two differing focal points allow a repeatable quick change of separate processing of the stand-alone-technologies by an oscillating movement. Thus none of them would affect the other e.g. otherwise the pellets could sublimate due to the laser beam before hitting the surface. Using the same focal point for both technology would be easier to realize.

While the laser can be applied de-focused for heating up the surface a focused laser application enables a defined processing of the surface. The de-focused laser prevents a cooling down of the workpiece. The higher temperature increases the thermal shock when the dry ice particles hit the surface and efficiency is improved. Therefore the wavelength has to be chosen according to the absorptance by the surface of the substrate. A focused laser application enables a defined surface structuring or smoothing of the workpiece. Thus a preliminary purification by dry ice blasting can be followed by a final laser processing cleaning step. It furthermore allows to combine the cleaning process with a potential following pre-treatment process (e.g. to realize a defined roughness). Both technologies can be applied in the same focal point or in different focal points.

3 EXPERIMENTAL SETUP

An easy-to-replicate standard was used to analyze the removal of highly adhesive coatings from faultily coated workpieces within the manufacturing process or the removal of partly remaining coatings from used products. A coating of PUR-2 components varnish with a thickness of 100 µm and 200 µm was defined as standard and applied in two layers, one white primer and a black finishing varnish. Plates of hot-dip galvanized steal with the dimensions of 150 mm x 50 mm were used as substrate. Furthermore the same plates were used to produce rusted specimen: The substrate material was exposed to a defined acidic atmosphere for a defined time.

For dry ice blasting the Artimpex device "Cryonomic Cab 52" was used. This device is based on the injection principle. For laser processing the "Dilas Diodenlaser 1500W" of Dilas Diodenlaser GmbH, Mainz was used. The diode laser has a wavelength of 940 ± 5 nm and a power output of 1500 W. The laser beam was focused to a field of 3.8 mm x 8 mm. Laser and dry ice blasting nozzle were adjusted to the same focus while the specimen was moved by a robot.

A thermographic camera system "Jade II MWIR" of CEDIP was added to the hybrid cleaning device to monitor the specimen's surface temperature. The camera determines temperatures from –30 °C up to 1500 °C by measuring the thermal radiation from 3 µm to 5 µm wavelength. It offers frame rates from 170 Hz up to 250 Hz and a high thermal resolution of less than 20 mK at 30 °C. It is important, that with regard to the shape of the specimen the thermographic camera must not be mounted within the range of the angle of reflexion of the laser beam. Figure 1 shows the final concept of the optimized hybrid cleaning device.

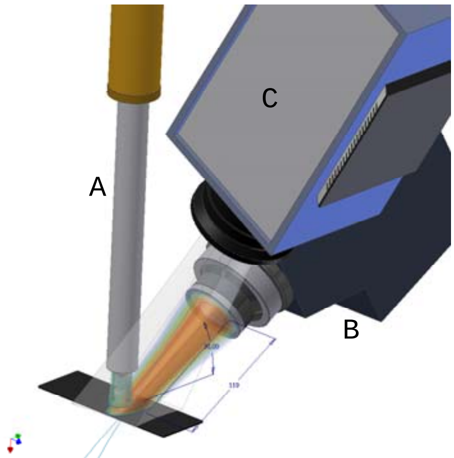

Figure 1: Concept of the hybrid cleaning device with dry ice blasting nozzle (A), diode laser (B) and thermography camera (C).

According to the results the optimized hybrid cleaning device includes a thermography camera. An angle of attack for the dry ice blasting of 90° and a blasting distance of 10 mm led to the best removal results. Figure 1 shows a relative small angle of attack of the laser system. This is necessary because of the dry ice blasting system – otherwise the blasting nozzle might be affected by the laser beam while the nozzle might reduce the energy induced to the specimen by the laser in return. A small angle of attack of the laser beam is possible while the specimen has a sufficient absorptance and the laser system is providing enough power.

By increasing the thermal mechanism of dry ice blasting the hybrid concept enables the reduction of the mechanic effect for specific cleaning tasks. Thus allows to lower the blasting pressure resulting in a reduction of the high sound pressure level. A link between the thermographic camera monitoring the specimen's surface temperature and the control of the laser power makes it possible to automate the control of the surface temperature. This offers new fields of applications where thermal sensitive materials are used.

To measure the removal rate the surface profile was detected perpendicular to the movement of the robot. Therefore the tactile measurement equipment "Talysurf-120L" of Taylor Hobson GmbH, Wiesbaden was used. The cone point of the applied sensing device had a radius of 2 µm and an angle of 60°. The cross sectional area (CSA) of the removed material was calculated based of the detected profile. For the calculation the software "Talymap Univ. 2.0.10" was used shown in Figure 2. Compared to a gravimetric measurement the applied method has the advantage of additional information about the material removal perpendicular to the direction of the robot movement. The volume-removal rate of the coating was calculated from the CSA and the individual feed speed of each test.

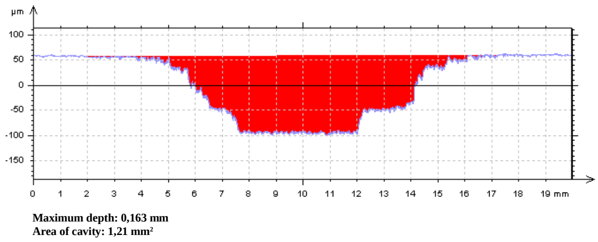

Figure 2: Calculation of the CSA based on a detected profile perpendicular to the robot movement.

First the dry ice blasting technology was optimized to reach the maximum material removal rate (blasting pressure, the distance between blasting nozzle and surface, the blasting angle and dry ice mass flow rate). The results are shown exemplarily in Figure 3.

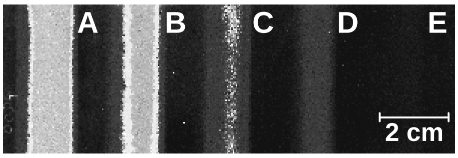

Figure 3: Optimization of dry ice blasting pressure: 12 bar (A), 10 bar (B), 8 bar (C), 6 bar (D), 4 bar (E).

For the hybrid technology these optimum process parameters could not be realized due to the dimensions of the equipment. The optimized dry ice blasting angle of 90° had to be adapted to 78° as well as the optimum blasting distance from 10 mm to 220 mm. A suitable feed speed was chosen by optical evaluation.

4 RESULTS OF EXPERIMENTS

The dry ice blasting parameters blasting pressure, blasting angle, dry ice mass flow rate and blasting distance were constant. First the stand-alone technologies laser (A) and dry ice blasting (B) were applied to compare the results with the hybrid technology (C) with the same process parameters of the combined technologies. Besides the coated standard explained above this test was also applied to a rusted specimen. The process parameters of laser processing, dry ice blasting and hybrid-dry ice blasting-laser processing are shown in Table 1.

Table 1: Process parameters

Feed speed:	
Coated specimen (Fig. 3)	60 cm per min.
Rusted specimen (Fig. 4)	14 cm per min.
Laser Parameters:	
Power	1077 W
Dry Ice Blasting Parameters:	
Blasting pressure	12 bar
Dry ice mass flow rate	60 kg/h
Blasting distance	220 mm
Angle of attack	78°

Figure 4 shows exemplarily the results of the material removal tests of a coated specimen while Figure 5 shows the results of the cleaning tests of a rusted specimen. The process parameters were identical, simply the feed speed was adapted to the different kind of specimen.

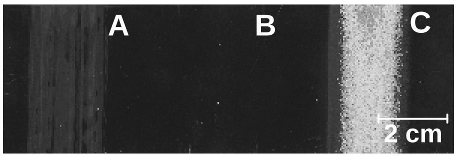

Figure 4: Comparison of cleaning results of a coated specimen by laser processing (A), dry ice blasting (B) and hybrid processing (C).

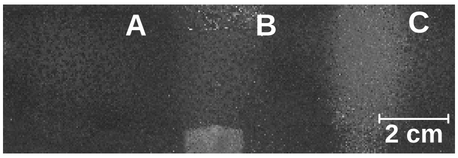

Figure 5: Comparison of cleaning results of a rusted specimen by laser processing (A), dry ice blasting (B) and hybrid processing (C).

Subsequently the results for the PUR-2 components varnish standard with a thickness of 200 µm are shown exemplarily. A comparison of the material removal of single dry ice blasting and hybrid laser assisted dry ice blasting is shown in Figure 6. The volume removal rate of the coating material is used as indicator.

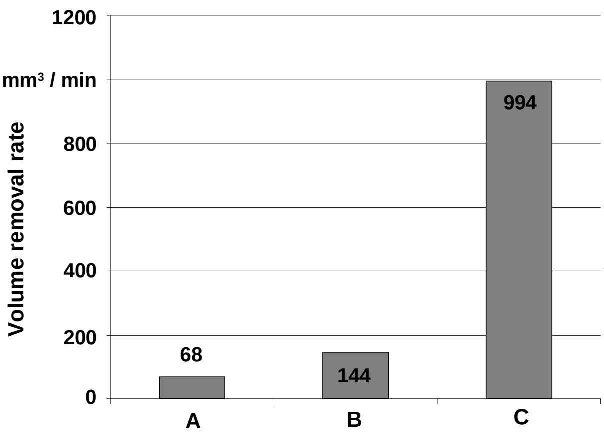

Figure 6: Volume removal rate of laser processing (A), dry ice blasting (B) and hybrid processing (C) of coating material of a coated specimen.

The diagram in Figure 6 shows the improvement of the volume removal rate of the hybrid process compared with the stand-alone technology dry ice blasting. The material removal of defocused laser processing is also shown to proof the synergetic effect of the combined technologies. The factor of volume removal rate of dry ice blasting compared with the hybrid process volume removal rate averages 6.9, an improvement of nearly 600 %. These results emphasize the potential of this hybrid combination.

With regard to Figure 5 these results show a great improvement of the cleaning process of rusted specimen. Nevertheless it is difficult to remove the rust completely. To remove the last percentage of rust is inefficient and therefore economically not advisable. In this regard the process parameters either have to be adapted or a specialized process has to be added. This could be done by focused laser application. The combination of dry ice blasting and Nd:YAG-laser processing was part of recent investigations [11]. Though the improvement of the material removal rate of focused Nd:YAG-laser assisted dry ice blasting is lower the focused laser application is apparently suitable for this final cleaning step.

5 SUMMARY

Dry ice blasting is an ecological alternative for conventional mechanical, chemical or aqueous cleaning and decoating methods. It is not suitable for highly adhesive or hard coatings and contaminants. By combining this technology with de-focused laser application the material removal rate of a defined testing standard was increased up to 600 % compared to the optimized stand-alone technology. It has to be researched if the optimized parameters of the stand-alone methods are also the ideal parameters of the hybrid combination.

It is planned to optimize the processing strategy of defocused laser application for the hybrid combination of both technologies. Particularly the cleaning and decoating of sensitive surfaces will benefit from this. Further tests are designated to research the combination of unfocused and focused laser application with dry ice blasting. The first process step may be used for preliminary purification that removes most of the contaminant of coating while the second process step will ensure a high purity grade.

ACKNOWLEDGMENTS

We extend our sincere thanks to the Deutsche Forschungsgemeinschaft. The investigations were carried out within the SfB 281 that is funded by the DFG.

Furthermore we extend our sincere thanks to all who contributed to preparing the instructions.

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