High pulse energy, kW average power nanosecond lasers enable breakthrough in rapid coating removal

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ABSTRACT

We demonstrate the use of kW class, high energy pulsed nanosecond lasers for surface cleaning applications. A hybrid ablation-detachment process allows removal rates of semi-transparent paint from primer at 40,000 $mm^3/kW{\cdot}min$. The process shows a threshold at which a nonlinear increase in removal rate is observed for energies above 100mJ for most paints. The impact of pulsed laser de-painting on substrates is examined.

Keywords: Laser cleaning, kW pulsed laser, laser depainting, laser material processing, laser rust removal

1. INTRODUCTION

The overall market for cleaning and preparation of surfaces is massive, easily 10's of billions of dollars worldwide and touches a wide range of industries ranging from transportation (automotive, aerospace and maritime), to energy (oil, gas, nuclear, solar, etc.) to industrial manufacturing and even the industrial food and beverage industry. Historically, much of this market is addressed by chemical and mechanical techniques such as solvent baths, media blasting (sand, ice, dry-ice, polystyrene, etc.) and water jet cleaning (i.e. pressure washing). There are some hybrid techniques, such as Xenon flash lamp assisted CO_2 pellet blasting which use the power of light to clean surfaces, however the direct use of photon-only based cleaning has historically been limited to niche applications where the relatively higher cost of ownership and low throughput are tolerable. Recently, with the rise of kW class, nanosecond pulsed laser platforms designed for operation in harsh industrial environments, this limitation on niche markets only is being lifted and industrial nanosecond lasers are finding their way into an ever-growing range of cleaning and surface preparation applications. In this work we focus on the benefits of such lasers in the area of paint removal.

As seen in Figure 1, laser based techniques for paint stripping provide wide ranging benefits compared to other techniques. These include reduction in volume of waste, minimizing impact on the substrate, agility of type of material removed, control on depth of penetration and facility safety requirements. The figure also points to one the main deficiencies of laser processing, namely the removal rate compared to these legacy techniques. The main reason for this deficiency is that most laser based removal techniques rely on direct ablation with high power CW lasers or rapidly scanned low energy nanosecond pulsed lasers. This means the lasers must ablate or burn through the entire layer of paint, resulting in relatively slow process times and requiring large amounts of laser power to complete removal on large surfaces such as aircraft or ships.

Recently[1], we demonstrated a unique mode of laser paint removal that instead relies on what is known as a detachment mechanism (Powerlase patent pending GB1710188.2). In this mode of operation, the laser light interacts with the boundary layer between the paint and substrate, creating a plasma which blows paint off the surface without the need to ablate the entire layer. This phenomenon results in a dramatic increase in productivity of the laser per kW of power. There are two added benefits to this mode of operation. First, because the removal occurs faster and with a relatively lower amount of laser power, the substrate temperature rise is lower. The benefit of this phenomenon is particularly high for substrates which are highly temperature sensitive, such as carbon fiber and fiberglass. The second ancillary benefit of the detachment method is that is produces a lower number of small particulates and other possibly toxic contaminants since the paint is not being completely combusted as is the case in the ablative methods. Details of these benefits are discussed later in this paper.

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The key to achieving the detachment method is the use of high per pulse energy lasers in the nanosecond regime while still maintaining enough average power to keep throughput high. As will be discussed later in the paper, we find a nonlinear behavior in ablation rate and a threshold-like behavior for the onset of detachment for energies in the range of 100mJ. Such high energies with kW average powers are produced by lasers such as Powerlase's Rigel series of industrial Nd:YAG lasers, which are capable of >250mJ fiber delivered pulse energy in nanosecond pulses at up to 1.6kW average power depending on repetition rate. These lasers are further optimized for de-painting and transformed into the Vulcan depainting system by including features such as a panel mounted GUI, extra-long delivery fibers of up to 100m and handheld beam delivery modules to allow remote cleaning (Figure 2).

Favorable — Moderate — Unfavorable

Approach → ↓ Characteristics	Diode Pumped YAG Laser	Xenon flashlamp with CO_2 Pellet blasting	High pressure water jet 32,000 psi	Plastic media or sponge blasting	Methylene Chloride
Special Facility Environmental Constraints	Eyewear protection	Eyewear / Ventilation	Yes	Yes	Hazardous chemical
Multi-Coating Layer Sensitivity	High	Low	Very Poor	Poor	Limited
Adaptable to Variety of Substrates	Excellent	Good	Moderate	Poor	Moderate
Paint Stripping Rate	Moderate	Moderate	High	High	Moderate
Substrate Intrusion Potential	Controllable	Moderate	High	High	Low
Total Waste Volume	Very Low	Low	Very High	Very High	High

Figure 1: Comparison of laser cleaning to other legacy techniques

Figure 2: Handheld high-power scanner (left) and Vulcan system (right)

2. HIGH ENERGY LASER DETACHMENT FOR DEPAINTING

Laser based detachment is a process well known in other industries dating back as far as the 1980's where it was used in the semiconductor industry[2]. Since then it has also been used in removal of transparent optical coatings from transparent substrates[3] and in partially-transparent paint removal[4]. Here we discuss the mechanism in the context of more common opaque paint removal, particularly white paint, which proves difficult to remove with other purely ablative techniques owing to its low absorption.

2.1 Basic Theory of Detachment

When paint is illuminated by an IR laser, most of the light transmits through the paint matrix with relatively weak absorption, scattering off opaque paint dye particles suspended in the mostly transparent polymer matrix of the paint. The light intensity decays along a simple Beer-Lambert law until it can interact with the substrate. When the intense nanosecond pulsed radiation interacts with the substrate (usually metal), the absorption properties dramatically change, as metal at the interface mostly absorbs the light, assisted by non-uniformities and defects in the surface. This results in ablation of the metal surface. However, the gas created in this ablation is trapped below the paint layer, creating build-up of pressure. If the substrate is thin enough and the interaction area is large enough, the pressure from this gas can explode the entire layer of paint from the substrate. Because of the confined space and high temperature of the gas, the pressures are massive and thus only a very small amount of material is ablated from the surface, leaving the substrate basically un-impacted by the removal. Figure 3 sketches this phenomenon and also shows the difference between a large and small beam, illustrating why this detachment phenomenon is more advantageous for high energy pulses. In the case of high energy pulses, a larger area can be illuminated with a uniform flat top beam, causing uniform ablation over a wide area of the substrate. This creates a geometric increase in the volume of gas produced while the strength of the region of coating is only increased linearly owing to the increase in length of the border of the beam. As a result the pressure and detachment force increases geometrically with the size of the beam provided ablation threshold can be reached. In summary, for small spot sizes and low energy the detachment force can often be too small to create detachment before ablation of the coating itself occurs, while with high energies, detachment can occur before the ablation threshold of the paint surface is reached. In the case of the Rigel lasers in this work (up to 250mJ pulse energy), pure detachment can be achieved for paints up to 100um thick. However, for thicknesses beyond this, the energy is dissipated too greatly before reaching the substrate, leading to an additional mechanism being required for thicker paints or multiple layers.

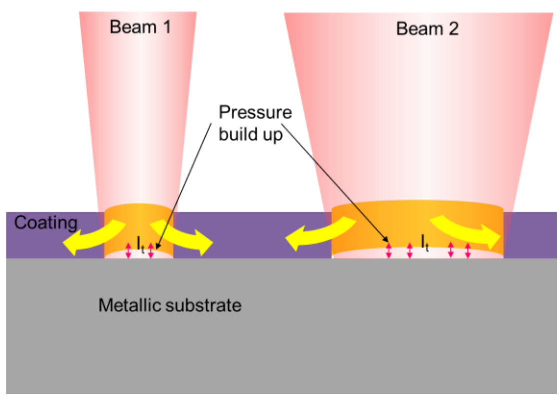

Figure 3: Sketch of detachment comparing large and small beams

2.2 Hybrid Detachment

When paint layers exceed 100um, a hybrid detachment mechanism must be used. In this case, as shown in Figure 4a, the detachment can only occur once several laser pulses irradiate the paint and directly ablate the thickness until the threshold for detachment can be reached and the pure detachment mechanism described above takes over. The hybrid mechanism further enhances the advantage of high energy pulses over lower energy pulses. This is explained in Figure 4b. Larger spot sizes enabled by higher energy already lower threshold for detachment compared to smaller, lower energy beams, but in addition, the higher energy can reach ablation threshold at the substrate and thus initiate detachment through a thicker section of paint than smaller energy pulses. This means that more individual pulses of ablation are needed with a smaller energy laser compared to the larger area higher energy laser, thus increasing the total time required to achieve detachment at a single point.

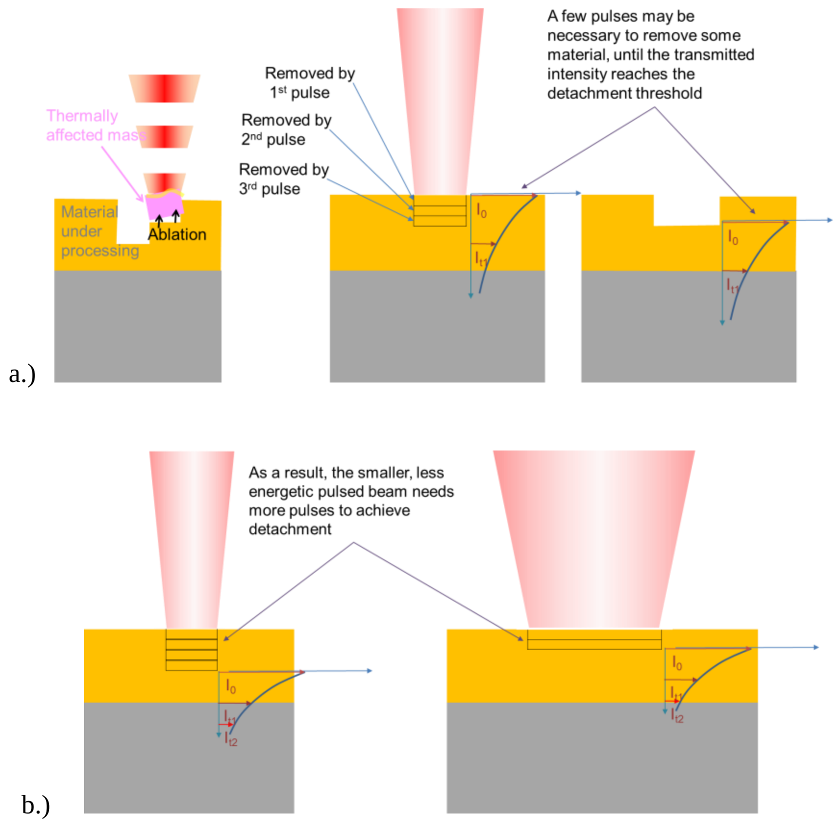

Figure 4: Sketch of hybrid detachment phenomenon. a.) Mechanism of hybrid detachment b.) comparison of high and low pulse energy

2.3 Experimental Detachment Results

To show the threshold-like behavior and dramatic increase in removal rates associated with detachment, we tested ablation on several different types of paint samples using a Rigel i1600 laser with up to 1600W average power and 270mJ pulse energy. We varied the spot size to keep fluence constant and adjusted the pulse energy of the laser. Pulse durations were in the 40-70ns range depending on the repetition ate used. Up to 160mJ could be achieved at 10kHz, so energies beyond 160mJ were achieved by lowering laser repetition rate to as low as 6kHz. Figure 5 shows the collection of this data. There is threshold-like behavior for the onset of a rapid increase in removal rate for energies on the order of 100mJ. The magnitude of the rate increase and the exact threshold for onset of detachment transition depends on the thickness of the layers as well as the color and composition. Primerless white paint showed a lower onset threshold, perhaps owing to a weaker bond to the substrate without the presence of a primer. White paint and primer show the fastest removal rates followed by yellow. Green and red paints show somewhat higher thresholds for onset of detachment. The reason for green and red having higher threshold compared to yellow is due to higher absorption of the IR light in green and red pigments. Higher absorption of light before it can reach the substrate will raise the threshold for detachment. As can be seen in the figure, removal rates of up to $0.4m^2$/min are achieved in relatively thick white paint and primer. White paint is the most difficult for purely ablative methods to remove, owing to the lower absorption. To see the speeds possible with even more energy and very thin paints, 270mJ was used to remove thin white paint and primer at nearly $1m^2$/min.

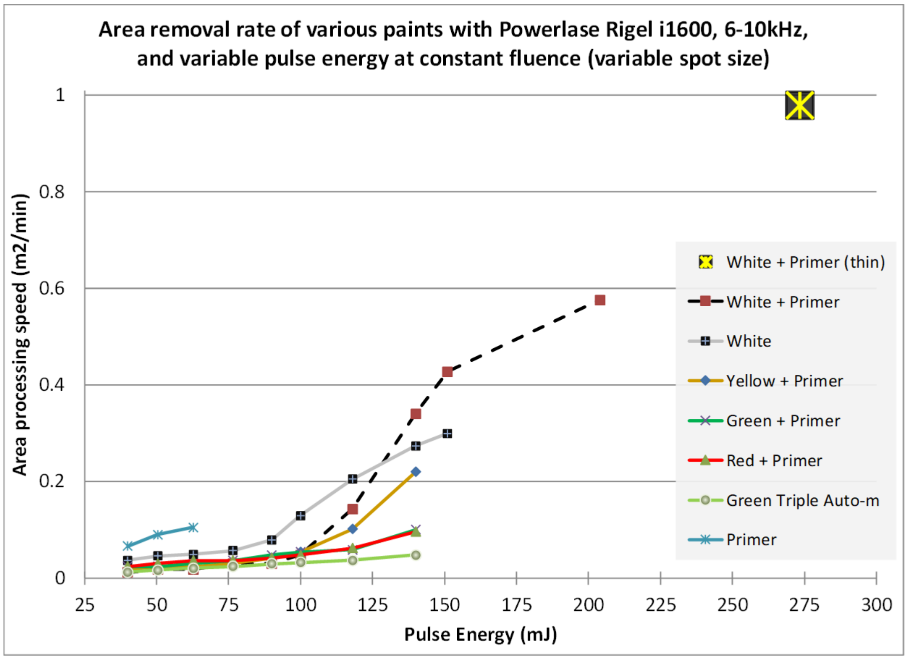

Figure 5: Removal rate data for various types and thicknesses of paint and paint/primer combinations

2.4 Improved Environmental Impact of Detachment

Though laser based depainting is substantially cleaner than legacy chemical and mechanical methods, there is also differentiation within laser depainting depending on method (i.e. either ablation or detachment). We conducted a study comparing the by-products of laser depainting. A vast array of possibly hazardous by-products are generated with organic paints, epoxies and primers are burned or ablated. To characterize this and compare detachment to ablation to purely thermal paint removal we monitored the presence of two species associated with thermochemical decomposition of paint and primer, Phenol and Xylene.

Table 1: Comparison of concentration of species generated during depainting for different laser based removal methods

	CO_2 or CW Fibre/YAG	λ=1µm, ns Pulsed <100mJ	λ=1µm, ns Pulsed >200mJ
Phenol	32 mg/m^3	26 mg/m^3	4 mg/m^3
Xylene	87 mg/m^3	63 mg/m^3	11 mg/m^3

Table 1 clearly shows the dramatically lower amount of species associated with thermochemical decomposition when depainting is done in the detachment regime (i.e. with pulse energies over 200mJ) compared to CW processing or even laser ablation in the regime below the detachment threshold. This is yet another advantage of the high energy detachment method.

3. STUDY OF IMPACTS ON SUBSTRATE

We have recently conducted a detailed study of a specific aerospace white paint and primer system and the following section covers the results of processing this specific material system and the properties of the surface when it is re-painted.

3.1 Sample Description

Substrate: 0.5 mm thick aerospace grade 2024 aluminum alloy sheet. The sheets were cut in square shape of 20x20 cm. A 6mm hole exists on one corner of the square, acting as a hanging hole during the paint drying process.

Coating: An Alocrom 1200 chromate conversion pre-treatment was applied on the aluminum sheets, giving them a yellowish tint. This is a typical process in the aerospace industry, it increases corrosion resistance and makes the surface ready for receiving a primer coating. The samples that have been repainted after laser depainting, have not be chrome converted again, they were just coated with the same paint system. The coating consists of a two-part yellow epoxy primer, namely the MIL-PRF-23377, and a glossy white, two component high solids polyurethane topcoat, namely the MIL-PRF-85285E TYPE 1 CLASS H, COLOR CODE 17925. Both coatings were spray painted. The primer was allowed to cure for 7 days and the topcoat for 14 days, as per manufacturer's directions. The combined thickness of the primer and paint varied from 56 to 72 μm, with an average of 64 μm.

3.2 Laser and Optical Setup

The performance characteristics of the laser system used are listed below.

- Model: Andritz Powerlase Rigel i1600
- Pulse repetition range: 5 to 15 kHz
- Pulse duration: 42 ns at 5 kHz, 64 ns at 10 kHz, 70 at 15 kHz
- Wavelength: 1064nm

The laser beam was delivered through 800 um core size process fiber. A dual axis galvo scanner mounted on vertical translation stage was used to adjust focal point and scan the laser on the Al plates which (figure 3) were laid on an XY translation stage for positioning.

Laser parameters considered in this trial are:

- Scanning speed for each scan.
- Pulse repetition rate, affecting pulse energy.
- Line to line spacing (see figure 6).
- Z-defocus affecting fluence and irradiance.
- Attenuator setting, affecting pulse energy and average output power.

Visual inspection of the scanned areas was carried out in terms of the amount of coating removed, color change on the coating and substrate, substrate reveal, substrate oxidation, substrate deformation, coating removal variance between overlap areas and non-overlap scans.

Measurements were carried out in terms of process duration, scan speed, line overlap, coating thickness and substrate temperature. The substrate temperature was measured using a thermocouple attached on the underside (non-illuminated side) of the plate.

Note: The scanner lens focal length was 163 mm, while the software was conducting calculations for an 80mm focal length lens. Hence the noted line speeds in the sample images represent actual linear speeds of twice the noted magnitude. The figures quoted in this report are the corrected figures for the 163 mm lens.

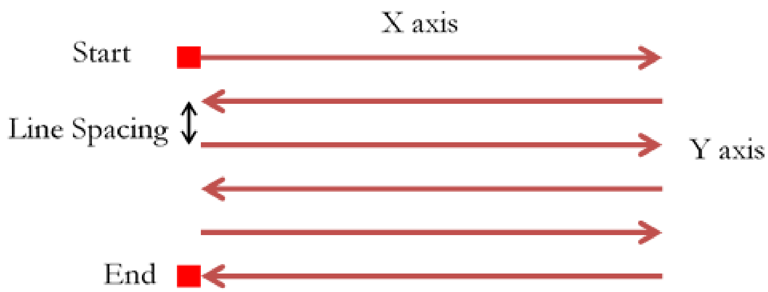

Figure 6: Removal rate data for various types and thicknesses of paint and paint/primer combinations

Coating adhesion testing

Pull off adhesion testing was carried out on plate samples after the original coating was applied and on selected laser depainted samples where 100% coating removal had been achieved. A Defelsko PositTest AT-A automated pull off adhesion tester, capable of testing up to 3500 psi, was used for the testing using 20mm diameter aluminum dollies. A cyanoacrylate (i.e. Superglue) type adhesive was used as recommended by the paint system manufacturer. The topcoat surface was only cleaned with methanol for the results presented here, as sanding the surface prior to adhesion gave results with more than 50% failure on the adhesive to topcoat interface. The aluminum dolly surfaces were always sanded with 200 grit sanding cloth and cleaned with compressed nitrogen and methanol.

Temperature measurement setup

The temperature of the 0.5 mm thick aluminum sheets was monitored during the laser paint removal processes, using a type K thermocouple, attached with tape on the underside of the sample. The thermocouple was relocated during each trial and positioned within a 2 cm radius from the center of the processed area and always within the scanning area.

3.3 Impact on substrate in comparison with process speed

All the results presented here were performed with 5kHz pulse repetition rate. The linear speed and raster line overlap were varied during processing, as well as the defocus position. The defocus position also affected the laser spot size diameter over which the laser pulses were released and consequently the peak fluence and peak intensity delivered to the sample surface. Figure 7 depicts the variation of peak intensity and spot size against the defocus height. In singe pulse processes it is typical to expect that with a defocused pulse and reduced peak intensity, process efficiency will be reduced. However, in the case of depainting where pulsed lasers are used with repetition rates in the several kHz range, the process features characteristics of both a pulsed laser process and a quasi-CW process.

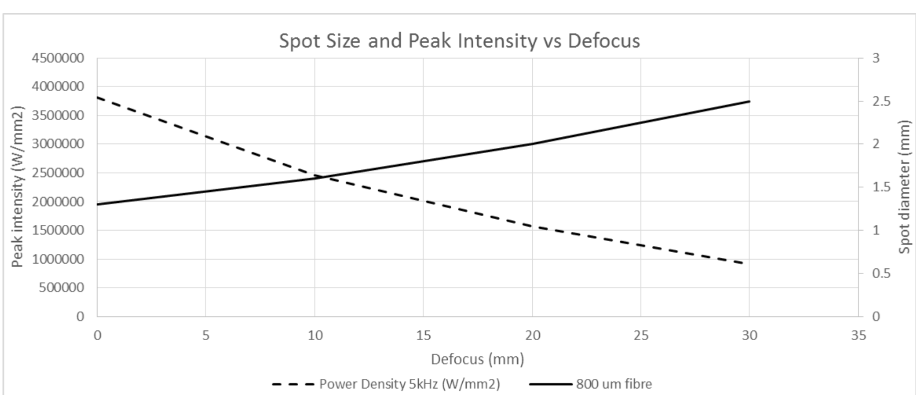

Figure 7. Variation of laser spot size diameter and pulse peak intensity, against distance from optimum focus of the f-theta scanning lens.

This is observed mainly for two reasons. First, because a large area detachment regime requires less peak intensity to be triggered, as explained above and second, that the large spot size area allows for larger scan lines to be made, which save many of the linear deceleration and acceleration delays of the scanner and thus covers surface faster with larger and quicker jumps from line to line. A comparison of process speed and coating removal percentage against line to line spacing (Figures 8.a to 8.d) reveals that larger spot size does increase the highest processing speed limit at which 100% coating removal is achieved. In the case of 20 mm defocus for example, the maximum process speed for full coating removal increases from 0.105 m^2/min for 0.53 mm line spacing, to 0.124 m^2/min for 0.63 mm line spacing, to 0.155 m^2/min for 0.84 mm line spacing and finally to 0.174 m^2/min for 1.26 mm line spacing. Beyond this line spacing, the distance of the lines becomes comparable with the size of the beam, measuring around 2 mm with the 800 μm fiber core size. As the beam intensity profile at such a defocus position starts to obtain a multimode Gaussian shape again, the intensity delivered at the edges of the Gaussian distribution is not effective enough for good coating removal. Therefore, increasing line spacing further results in loss of process speed efficiency as the removal is now incomplete between the raster lines. The same occurs for a defocus of 10 mm (Figure 8.b), where the process speed increases from 0.178 to 0.192 m^2/min with an increase of line spacing from 1.05 to 1.26 mm respectively. At 1.68 mm line distance, the raster lines occur at distances longer then the beam diameter of 1.6 mm, thus removal efficiency is disrupted. In this situation however, the beam intensity profile is closer to the top-hat distribution expected at the exit of the fiber and as a result close to the f-theta focus. Hence the limit is closer to the size of the beam. Examining the case of a larger defocus at 30 mm (figure 8.d), the maximum process speed capable of 100% coating removal is feasible with a line spacing of 1.47 mm, which is much smaller than the 2.5 mm measured spot size, compared to the tests closer to the focus. This is attributed to the spreading of the beam intensity distribution and lowering of the Gaussian “wings” of the profile. Moreover, at this defocus, beam intensity drops enough to start affecting the efficiency of hybrid removal and more ablative pulses need to be released per unit surface until detachment can take place, or detachment is completely suppressed. For the case of processing at focus, the highest processing speed at 100% coating removal is anticipated to be achieved with a line spacing closest to the spot size (figure 8.a). As a result, process speed does increase with an increasing spot size, but this progress is limited by the total pulse energy available by the laser source. Hence, if the laser source could achieve pulse energies in the 300 and 400 mJ, instead of the current limit of 260 mJ, the line to line speed and spot size could be increased further, while maintaining the hybrid detachment advantage in increasing process speed efficiency, until the intensity distribution dropped enough to inhibit hybrid detachment.

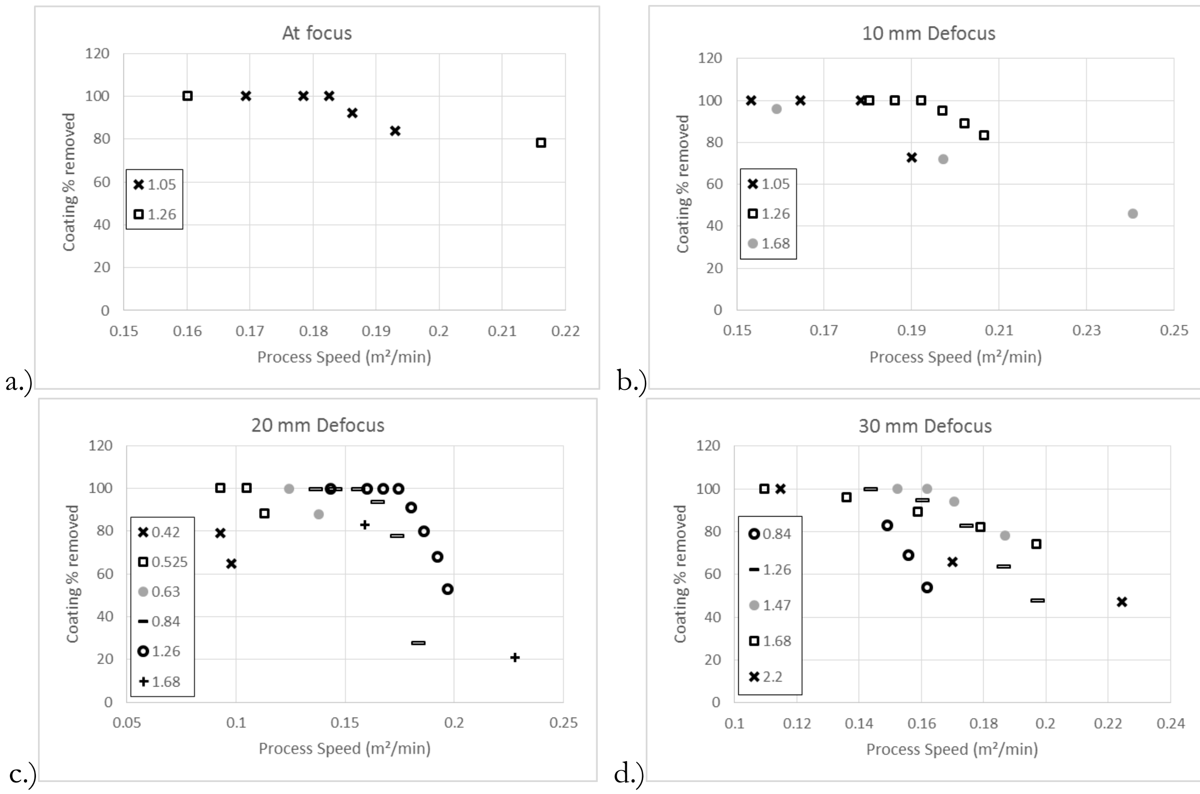

Figure 8. Coating percentage removed in different process speeds, results grouped by line to line spacing. a) Processing at focus, b) processing at 10 mm defocus, c) processing at 20 mm defocus, d) processing at 30 mm defocus.

The painted samples were tested for coating adhesion, prior to laser depainting, using the pull off method. 8 sites were tested on 3 different sheets. The pull off pressure measured varied with a standard deviation of 83.3 PSI and averaged at 1823 PSI. Figure 9 shows the scatter of measurements across the test sites. The variation of results is attributed to coating inconsistencies and adhesive boding inconsistencies. Most of the failures demonstrated a >70% substrate to primer adhesive failure, with 5 to 20% of primer cohesive failure and 15 to 5 % adhesive failure of the adhesive to the test dolly, usually occurring towards the edges of the dolly.

Plotting pull off adhesion test results conducted on areas that have been repainted after laser depaint, across various process speeds (figure 10), mainly reveals that the adhesion achieved comes close to the average measured on originally painted surfaces, although all the values are below this 1823 PSI average. The results are grouped per defocus in figures 10 and 11. The spread of measured pull off pressures ranges from 1086 to as high as 1774 PSI. Adhesion failures were noted mainly at the substrate to primer interfaces, from 55 to 80 %. Cohesion failure in the primer was also significant ranging between 40 and 10 %.

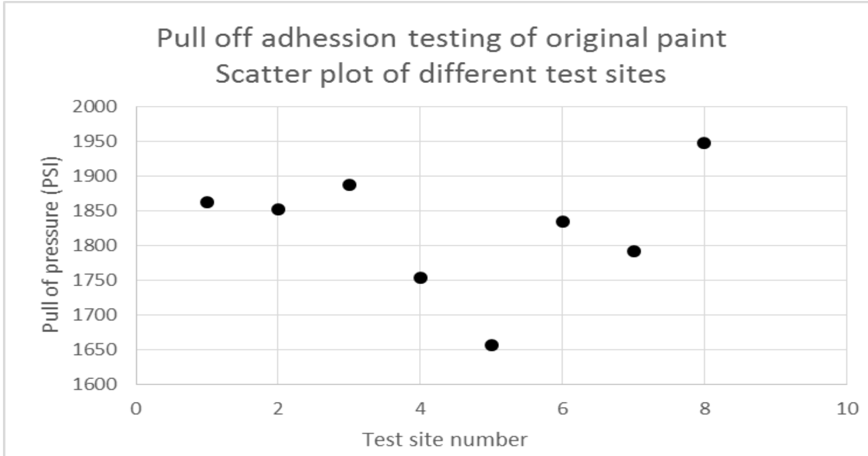

Figure 9. Distribution of pull off adhesion test measurements over 8 sites of painted samples prior to any laser depainting.

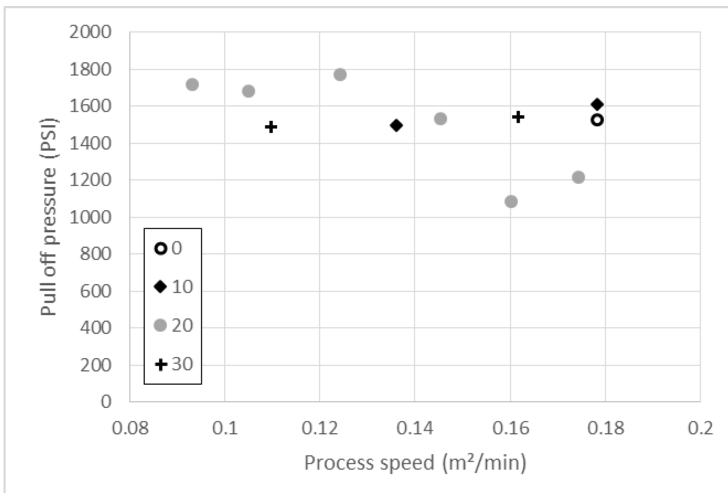

Figure 10. Pull off adhesion test results grouped by defocus and plotted against process speed.

By plotting the values against line spacing (figure 11) the observation that can be made is that there is higher adhesion at line spacing of 0.5 to 0.6 mm and a grouping of test results in that region, around the 1700 to 1800 PSI. This indicates that closer line spacing, regardless of the speed of processing may have beneficial results for coating adhesion after laser depainting. The adhesion achieved with small distance line spacing is quite close to the 1823 PSI average of the original coating. Adhesion at higher speeds is within 350 PSI of the original coating adhesion strength average, indicating that it might be possible to improve by adjusting the paint removal methodology. However, the results presented here are too few to offer fully conclusive arguments towards any approach and mainly indicate proximity of adhesion strength after laser depainting has been applied at high speeds without further surface preparation. Images in Figure 12 depict the laser depainted sites with 1.26 and 0.53 mm line spacing, prior to being re-coated. 100 % coating removal had been achieved in both cases, leaving behind the aluminum surface and some amount of the original chromate conversion.

Finally, it is interesting to note that in all the tests performed the temperature measured underneath the processed area of the aluminum sheet, never exceeded 95 ºC. For samples processed with speed beyond 0.09 m^2/min, the temperature was below 45 ºC. The aluminum sheets used were only 0.5 mm thick and considering the good thermal conductivity of aluminum of 233 W.m-1.K-1, this temperature is considered representative of the bulk of the aluminum sheet during processing. Furthermore, sanding scratches that were inflicted during surface preparation of the plates prior to painting, were fully maintained after fast laser processing with defocus of 10 and 20 mm. This indicates that the initial structure of the surface and mechanical properties of the metal alloy are well maintained after laser processing.

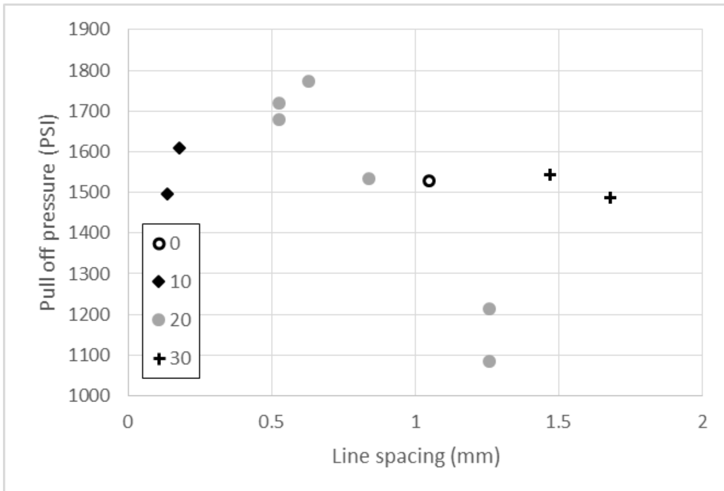

Figure 11. Pull off adhesion test results grouped by defocus and plotted against line spacing.

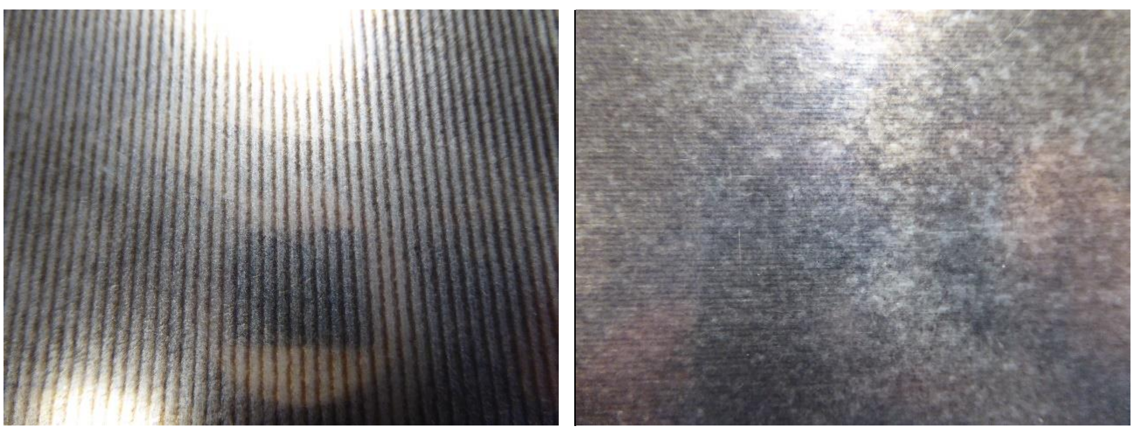

Figure 12. Left) laser depainted site with line spacing of 1.26 mm, 100 % coating removal. The darker lines are remaining chromate. Right) Laser depainted site with line spacing of 0.53mm, 100 % coating removal.

4. DISCUSSION AND CONCLUSION

In summary, we have demonstrated the value of high energy and average power pulsed lasers in depainting by way of a detachment or hybrid detachment mechanism. In some cases, removal rates of upwards of $1m^2$/min were realized. The theory behind the detachment and hybrid detachment methods have been discussed and as have the benefits of these methods compared to other laser based depainting methods.

To show a specific example of detachment in a practical application, we investigated the removal rate, impact to substrate and temperature rise on an industry pertinent sample of aerospace paint on aluminum substrate. The increase in process speed anticipated due to hybrid detachment is observed when increasing processing spot size and raster line distances. The increase is speed seems to be limited by the pulse energy available by the laser system. Paint removal process speeds of up to 0.19 m^2/min have been recorded on two-layer paint systems including a white top coat high in solids and primer, totaling a combined coating thickness of 64 μm in average. The surfaces recoated with the same paint system after laser depainting exhibited coating adhesion strength comparable to that of coatings applied on non-laser depainted surfaces and in some cases the variance is less than 5%. Temperature rise recorded during laser processing did not rise beyond 45 ºC when processing with speeds above 0.1m^2/min, and original surface features are preserved after fast laser depainting. The process represents a fast and low impact solution to support future laser cleaning needs of the aerospace industry.

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