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# Decoating operations for repurposing end-of-life (EOL) automotive metal sheets

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**Abstract.** This article considers a process for repurposing panels from end-of-life automobile body parts. The process is based on flattening, a plastic deformation operation that can be realised with a hydraulic press equipped with flat dies. Focus is placed on automotive coatings. Four automotive coatings removal methods are considered and analysed, namely: chemical decoating, mechanical decoating by brushing, mechanical decoating by grinding and laser decoating. A comparison in terms of quality and productivity is then made. From experimental results, mechanical decoating by brushing and mechanical decoating by grinding are the most appropriate among considered removal methods respectively for high productivity and high quality requirements.

## Introduction

This article considers a process for repurposing panels from end-of-life (EOL) automobile body parts. The process, which has been introduced in [1] and further analysed in [2], is based on flattening.

The goal of this process is to manufacture products using EOL automobile body panels, reducing or eliminating the need for new raw materials such as steel and aluminium, thereby minimising greenhouse gas emissions and environmental pollutants. The process is composed of several operations including flattening, decoating, reworking and recoating, as illustrated in Fig. 1.

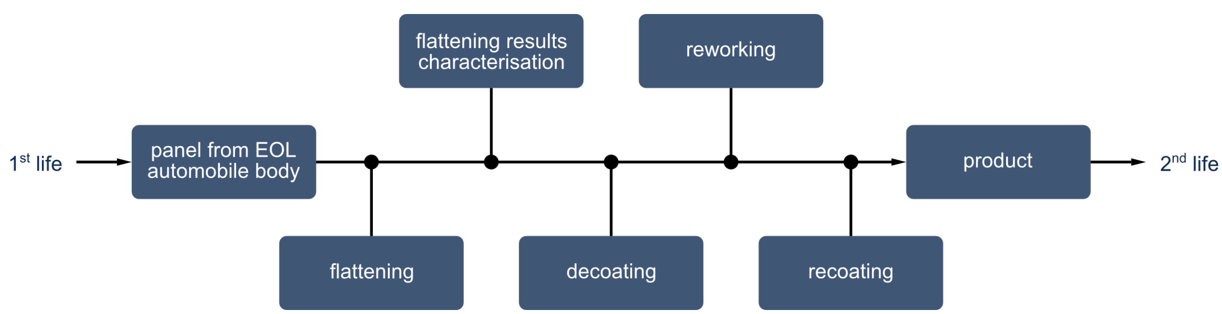


*Figure 1 – repurposing process illustration*

After a brief description of flattening, focus is placed on decoating. Four automotive coatings removal methods are considered and analysed, namely: chemical decoating, mechanical decoating by brushing, mechanical decoating by grinding and laser decoating. A comparison in terms of quality, productivity and energy consumption is then made.

## Flattening

Flattening is a plastic deformation operation used to restore metal sheets flatness, which can be realised with a hydraulic press equipped with flat dies, as illustrated in Fig. 2a. Flattening results can be assessed using a profile measurement system. Indeed, acquiring metal sheets surface profile information on flatness can be extracted.

For this study, a hydraulic press allowing control on dwell force (the force applied on the metal sheet), up to 400 ton, dwell time (the duration of force application) and dies temperature, up to 300 °C, has been used.

Besides, a profile measurement system based on laser triangulation principle, reported in Fig. 2b where a coordinate system of axes $x$, $y$ and $z$ is also introduced, has been used. The system allows non-contact profile measurements. A screw mechanism driven by an electric motor moves a Wenglor MLWL131 laser triangulation sensor in $y$ axis direction; at each $y$ coordinate value, the sensor acquires a set of $x$-$z$ coordinates values, resulting in a cloud of points that describes the metal sheet surface profile.

Images of a sample metal sheet and its surface profile, acquired with described system before and after flattening are provided in Fig. 3a and Fig. 3b respectively.

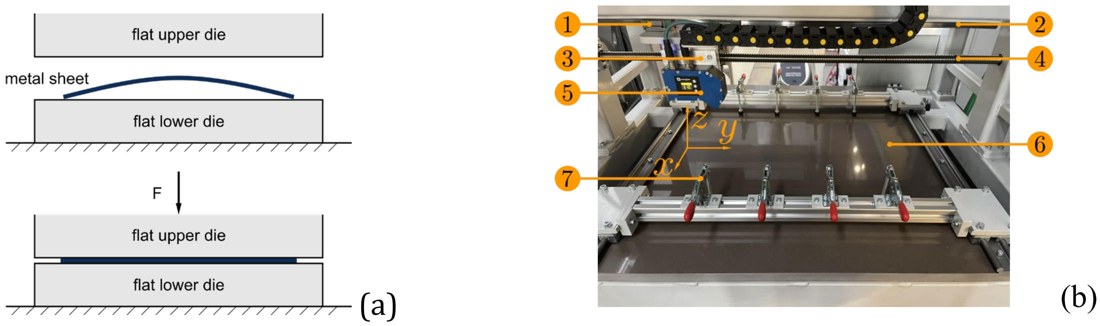


*Figure 2 – (a) flattening operation illustration (b) profile measurement system components: 1. roller, 2. roller guide, 3. lead nut, 4. lead screw, 5. laser triangulation sensor, 6. support plane, 7. clamping devices*

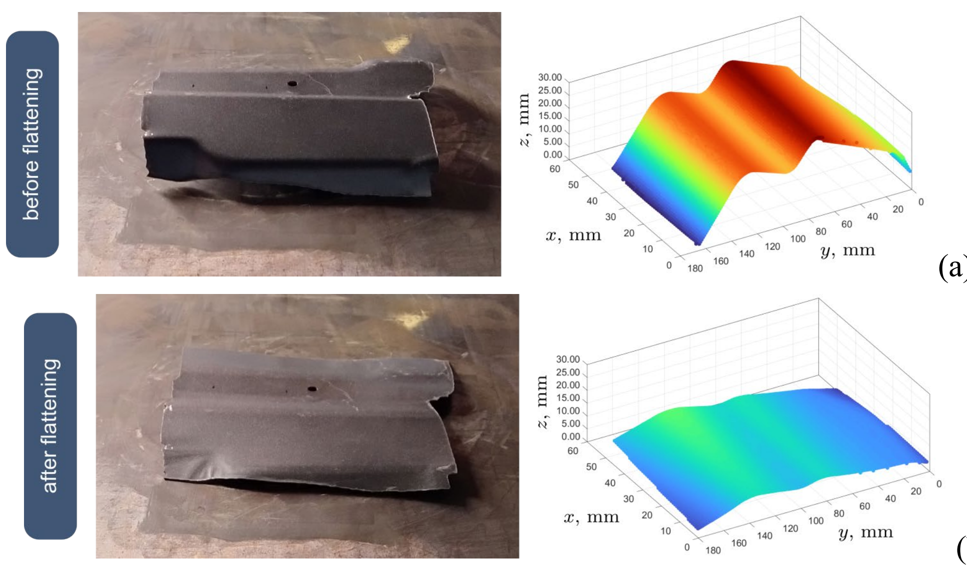


*Figure 3 – sample and associated surface profile before flattening operation (a) and after flattening operation (b)*

**Automotive coatings removal methods**

Automotive coatings consist of multiple layers, each with distinct functions, characteristics and application methods [3], [4]: conversion layer (2-5 μm), electrodeposited layer (25-30 μm), primer (30-40 μm), basecoat (15-25 μm) and clearcoat (35-50 μm). The automotive coating system protects the substrate from corrosion and has an aesthetic function.

While automotive coatings removal is common in repair shops, there is limited scientific literature on the subject.

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Chemical decoating. Chemical decoating involves applying a chemical to the coating. Depending on the chemical and the coating properties, different phenomena can occur [5]:

- Coating dissolution: the coating dissolves into the chemical, forming a solution
- Coating degradation: a chemical reaction occurs between the chemical and the coating resulting in its degradation
- Coating adhesion degradation: the chemical reaches the substrate diffusing through the coating or exploiting damages in the coating resulting in a loss of adhesion between the substrate and the coating

Mechanical decoating. Mechanical decoating includes brushing and grinding, both of which are machining processes; brushing removes material using wires, while grinding removes material using abrasive grains. In general, mechanical decoating methods can result in [6], [7]:

- Elastic deformation without material removal: the coating undergoes elastic deformation without being removed
- Plastic deformation without material removal (ploughing): the coating undergoes plastic deformation without being removed
- Plastic deformation with material removal: the coating is removed by shearing with chip formation

Laser decoating. Laser decoating involves different material removal mechanisms, primarily influenced by the following factors [8]:

- Irradiance: the power absorbed by the workpiece per unit area of the laser beam spot
- Interaction time: the duration of workpiece-laser beam interaction

Specifically, with continuous wave laser or long pulsed wave laser material removal occurs by heating and vaporisation while with high irradiance short pulsed wave laser material removal occurs by ablation [9], [10].

**Materials and methods**

Materials. For decoating experiments samples taken from two different automobile models have been used, they will be termed samples type 1 (aluminium substrate, blue colour) and samples type 2 (steel substrate, red colour).

A characterisation of available samples in terms of thickness and type of layers composing the coating system has been attained analysing samples cross section with Alicona Infinite Focus G4. Results are reported in Fig. 4a.

Chemical decoating. A commercially available chemical for ferrous and non-ferrous substrates containing 1,3-dioxolane, n-butyl acetate and 2-butanone [11], has been applied on both samples type 1 and samples type 2:

- three sample preparation types (factor A): no preparation (level 0), homogeneous mechanical preparation through mesh number 80 abrasive paper (level 1) to partially remove the clearcoat which provides protection from chemical attacks [12] and thermal preparation through warm flattening (level 2) to cause a decrease in adhesion strength and cohesion strength of the coating system
- three chemical dwell times (factor B): 15 min, 30 min and 45 min

have been considered ($3^2$ factorial experiment).

Concerning thermal preparation, warm flattening parameters have been selected after experimental trials aiming at achieving substrate flatness and coating system adhesion/cohesion degradation. Specifically:

- A dies temperature of 280 °C and a dwell time of 10 s have been selected for both samples type 1 and samples type 2 to keep the thermal load on the coating systems constant
- A dwell force of 60 ton has been selected for samples type 1, while a dwell force of 120 ton has been selected for samples type 2; a greater dwell force was necessary for samples type 2

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compared to samples type 1 due to the greater yield strength of steel substrate (of samples type 2) compared to aluminium substrate (of samples type 1)

Photographs of sample preparation types are provided in Fig. 4b.

For each tested condition a process yield $Y$ (response variable not greater than 1) has been calculated. A photograph has then been taken of each sample and analysed using colour thresholding, an image segmentation technique that allows partitioning a set of pixels in subsets of pixels based on pixels colour coordinates and user-selected colour coordinates thresholds. With this technique it has been possible to detect pixels where clearcoat, basecoat and primer removal occurred, assigning them white colour coordinates, and pixels where it did not, assigning them black colour coordinates. Then, process yield $Y$ has been calculated as reported:

$$Y = \frac{n_{\mathrm{wp}}}{n_{\mathrm{wp}} + n_{\mathrm{bp}}} \quad (1)$$

being $n_{\mathrm{wp}}$ the number of white pixels and $n_{\mathrm{bp}}$ the number of black pixels.

Mechanical decoating. Both for sample type 1 and for sample type 2, one brushing test and three grinding tests (termed A, B, C) have been performed.

In brushing tests, a cup brush with non-twisted steel wires has been used.

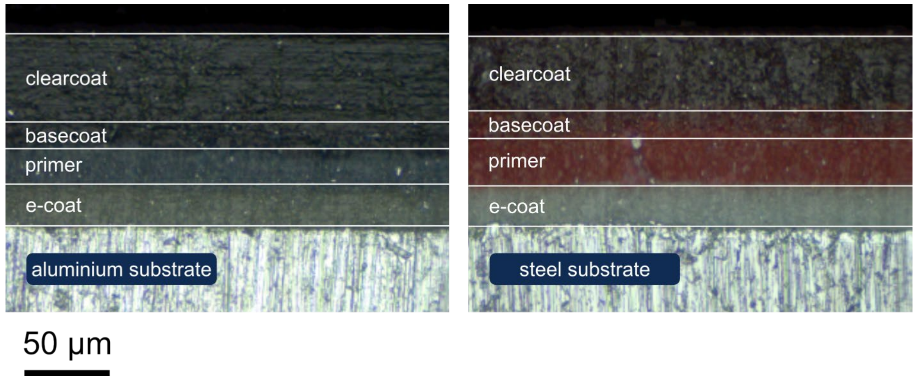
In grinding tests, grinding disks of different mesh number (finer to coarser going from grinding test A to grinding test C), made of non-woven nylon fibres and silicon carbide abrasive grains bonded with a synthetic resin have been used.

In both brushing tests and grinding tests, a drilling-milling machine equipped with a proper tool, depending on considered test, and a 2 axes worktable, on which samples have been fixtured, have been used.

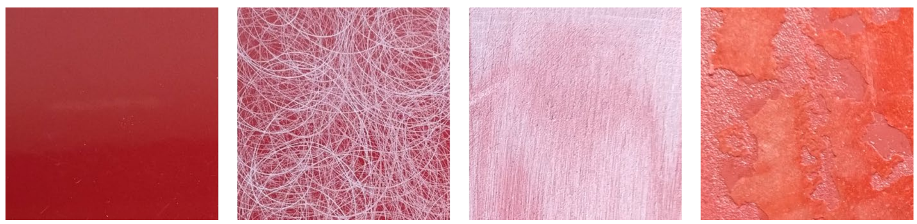
A spindle speed of 515 rpm has been selected, it was the minimum spindle speed available with used drilling-milling machine. It has been decided not to increase spindle speed to limit working temperature and tool wear.

Laser decoating. Tests on samples type 1 and samples type 2, with no preparation, non-homogeneous mechanical preparation (mesh number 80 abrasive paper has been used stopping before a homogeneous result was achieved), to promote coating fracture in laser decoating operation, and homogeneous mechanical preparation (mesh number 80 abrasive paper has been used stopping when a homogeneous result was achieved), to promote laser beam absorption, have been performed. Photographs of sample preparation types are provided in Fig. 4b.

A Netalux Needle 100 watts machine (Nd:YAG laser source, wavelength 1064 nm, pulse duration 150 ns, selected pulse frequency 100 kHz, selected power 100 W) and a fumes extraction system have been used.




*(a)*



*(b)*

*Figure 4 – (a) cross section images of a sample type 1 (on the left) and type 2 (on the right) (b) sample preparation types (photographs of samples type 2, equal preparation types have been realised on samples type 1), from left to right: no preparation, non-homogeneous mechanical preparation, homogeneous mechanical preparation, thermal preparation*

**Results and discussion**

Chemical decoating. From analysis of variance (ANOVA) with significance level $\alpha = 0.05$, sample preparation type (factor A), chemical dwell time (factor B) and their interaction have a significant effect on process yield (square root transformed to meet ANOVA hypotheses) with $p$ values $< 0.01$, for both sample type 1 and sample type 2. Based on Tukey method with $\alpha = 0.05$ and if time has to be minimised, thermal preparation with a chemical dwell time of 15 min, for sample type 1, or 30 min, for sample type 2, has to be selected.

With chemical decoating, residues which might have been degraded in terms of adhesion strength and cohesion strength by the applied chemical are left on the substrate (Fig. 5a) requiring a mechanical post-processing. Furthermore, chemical decoating poses concerns for operator health and environment, producing hazardous waste that must be properly disposed.

Based on these results, chemical decoating is not considered an adequate option for the examined repurposing process.

Mechanical decoating. With both brushing and grinding, a complete coating system removal has been achieved on both sample type 1 and sample type 2 (Fig. 5b), therefore both processes are considered adequate options. Nonetheless, some issues have been detected.

- A first issue is non-flatness of metal sheets as tests were performed before flattening, that has resulted in a non-constant depth of cut causing difficulties in tool positioning in tool axis direction. Possible remedies are to perform decoating after flattening and to introduce a force control system that would allow keeping the force in tool axis direction, applied by the tool on the metal sheet, constant and equal to a previously defined optimum value. In general, wire brushes can adapt to non-flatness better than grinding tools, as a result this issue is less relevant in brushing than in grinding
- A second issue is dust. It poses risks for operator health, must be properly disposed and can cause tool clogging, which results in a decrease or loss in material removal capability. A dust extraction system is therefore required

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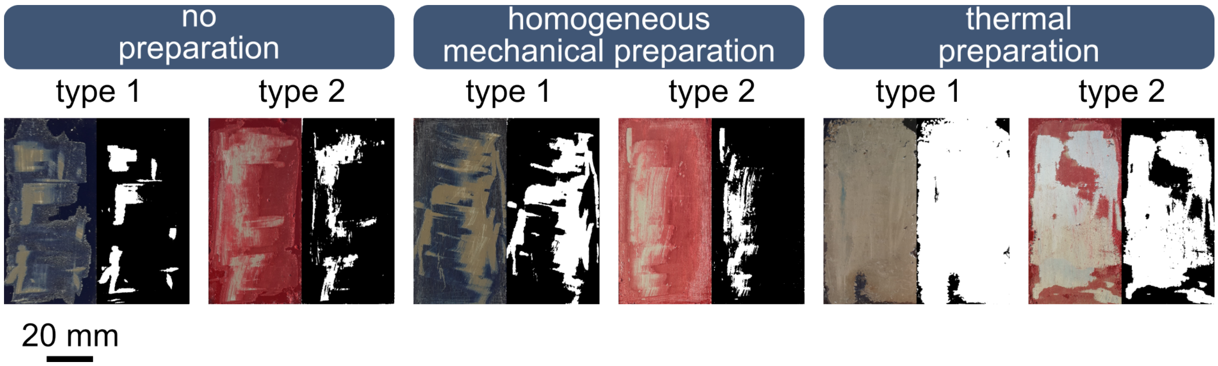


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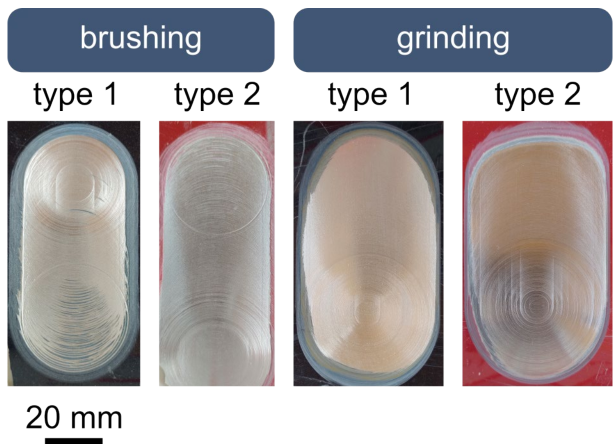


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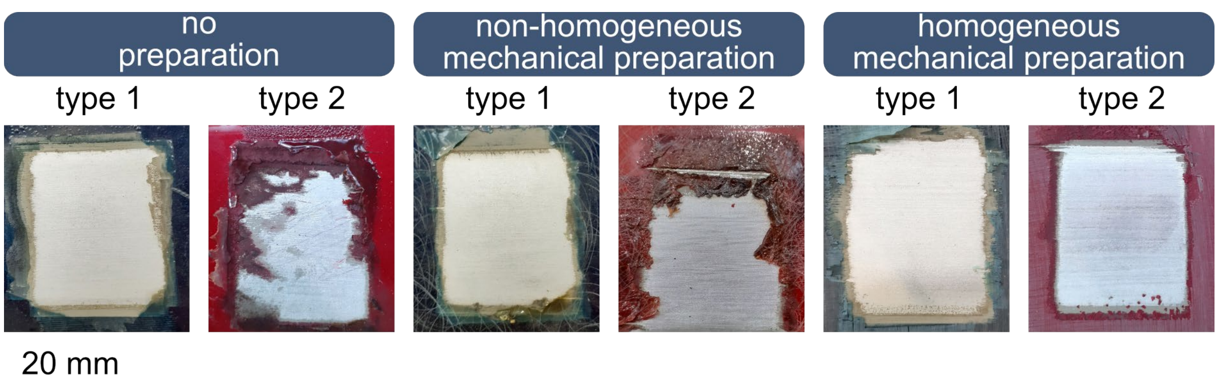


*(c)*

*Figure 5 – (a) examples of results of chemical decoating tests (with a chemical dwell time of 30 min) (b) results of brushing test and grinding test C (comparable results have been obtained in grinding test A and grinding test B) (c) results of laser decoating tests*

Laser decoating. Considering laser decoating, a complete coating system removal has been achieved on both sample type 1 and sample type 2 (provided that a proper preparation is performed, Fig. 5c), therefore laser decoating is considered an adequate option.

Nonetheless, some issues have been detected.

- A first issue is non-flatness of metal sheets as tests were performed before flattening, that has resulted in a non-constant stand-off distance (SOD) causing laser beam defocusing. Possible remedies are to perform decoating after flattening and to introduce a SOD control system that would allow keeping the SOD constant and equal to a previously defined optimum value

- A second issue is delamination, i.e. loss of adhesion between layers of the coating system. It has resulted in layers lifting without removal and therefore in shielding underlying layers from incident laser beam. When delamination occurred, it was necessary to use a spatula to remove lifted material before continuing with laser decoating operation
- A third issue is ignition of a combustion reaction between the coating system and air. It is a hazard for operator health and working environment and can have a negative effect in terms of process quality
- A fourth issue are fumes. They are a hazard for operator health and can have a negative effect in terms of efficiency by scattering and absorbing incident laser beam resulting in an increase in required number of passes. A fumes extraction system is therefore required

By introducing a flow of inert gas parallel to workpiece surface, an inert atmosphere would be produced in the process zone; combustion reactions would be avoided, besides fumes extraction would be assisted.

Described issues with laser decoating can be observed in Fig. 6.

*Figure 6 – delamination, ignition of a combustion reaction and fumes in a laser decoating operation*

**Decoating methods comparison**

The decoating methods were compared based on quality, evaluating surface roughness Ra, and productivity, evaluating material removal rate MRR; surface roughness was measured using a Mahr Perthometer PGK, while material removal rate was calculated as follows:

$$\mathrm{MRR} = \frac{V}{\Delta T} \tag{2}$$

being $V$ the volume of material that is removed and $\Delta T$ the time interval that is required by considered process to remove it.

Besides, energy consumption per unit volume of removed material, i.e. specific energy consumption $e$, has been calculated for each of considered decoating methods as reported:

$$e = \frac{P}{\mathrm{MRR}} \tag{3}$$

being $P$ the power required to operate the machine used for decoating operation and MRR the material removal rate. Not having a power measurement system, maximum values of power provided by machines manufacturers (880 W for adopted drilling-milling machine, 600 W for adopted laser machine) have been considered for the analysis, therefore resulting values of specific energy consumption have to be considered as maximum values of specific energy consumption

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with adopted machines. Furthermore, auxiliary systems (e.g. dust extraction system, fumes extraction system) have not been considered in the analysis.

The comparison has been limited to brushing, grinding and laser decoating; chemical decoating has not been considered due to obtained results in chemical decoating experiments, which are not considered adequate as described in previous section.

For each decoating method, the mean surface roughness Ra, material removal rate MRR and specific energy consumption *e* have been calculated; results are provided in Fig. 7.

Surface roughness Ra decreases from brushing to laser decoating to grinding, hence grinding is the most appropriate method when high quality is required.

Material removal rate MRR increases from grinding to laser decoating to brushing, hence brushing is the most appropriate method when high productivity is required.

Specific energy consumption *e* decreases from grinding to laser decoating to brushing, hence brushing is the most sustainable option in terms of energy consumption.

With laser decoating, intermediate results in quality, productivity and energy consumption have been obtained. Nonetheless, laser decoating remains a valid option as it produces less waste than other decoating methods, it could allow a selective removal of coating layers [13] and it could be used for surface texturing to enhance tribological behaviour (for following reworking) or coating adhesion (for following recoating) [14].

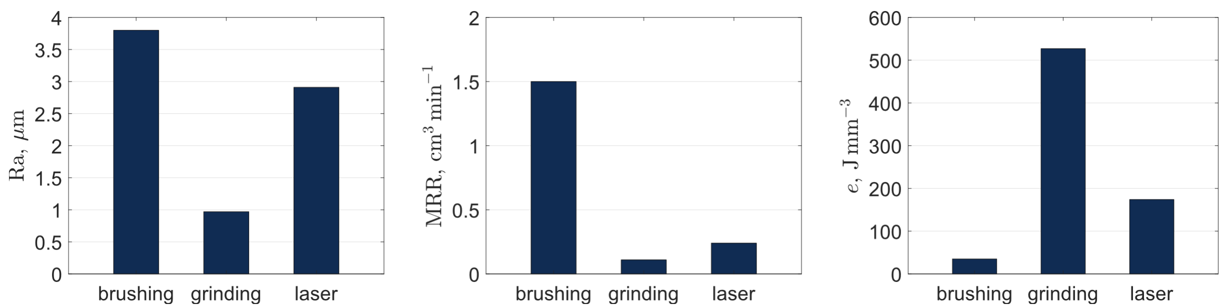


*Figure 7 – mean surface roughness Ra, material removal rate MRR and specific energy consumption e for each decoating method*

## Conclusions

In this article, four automotive coatings removal methods have been analysed and compared in terms of quality, productivity and energy consumption. Based on experimental results:

- With chemical decoating, residues which might have been degraded in terms of adhesion strength and cohesion strength by the applied chemical are left on the substrate requiring a mechanical post-processing. Furthermore, chemical decoating poses concerns for operator health and environment, producing hazardous waste that must be properly disposed. Hence, chemical decoating is not considered an adequate option for the examined repurposing process
- With both brushing and grinding a complete coating system removal has been achieved. Hence, both brushing and grinding are considered adequate options. Nonetheless, issues as non-flatness of metal sheets and dust have been detected. Possible remedies have been provided. Among considered decoating methods, brushing and grinding are the most appropriate respectively for high productivity and high quality requirements
- With laser decoating a complete coating system removal has been achieved. Hence, laser decoating is considered an adequate option. Nonetheless, issues as non-flatness of metal sheets, coating system delamination, combustion reaction ignition and fumes have been detected. Possible remedies have been provided. Despite intermediate results in quality, productivity and energy consumption, laser decoating remains a valid option as it produces

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less waste than other decoating methods, it could allow a selective removal of coating layers and it could be used for surface texturing to enhance tribological behaviour or coating adhesion

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