Feasibility Study of A New Approach to Removal of Paint Coatings in Remanufacturing

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Abstract: Environmental issues are recognised as being increasingly important, especially in the 21st century; researchers have thus proposed remanufacturing as a means of improving manufacturing sustainability. Cleaning the end-of-life products, that saves commercial values, is one of the most demanding steps and is usually one of the most polluting stages. Product surface coatings, are especially difficult to remove, in this process, because they have been designed to be robust during the service. Traditional methods, aqueous cleaning for instance, are either water consuming or use large amounts of chemical cleaning agents, which are obviously environmentally unfriendly. In this paper, a new approach to removing the paint layers on the surface of the retired product is proposed. The cleaning uses supercritical carbon dioxide ($SCCO_2$) as the pre-treatment, and then wet shot blasting cleaning removes the residues on the treated surfaces. It is difficult to get paint layers in the same condition and the real products are too big for the experimental platform. Experiments were thus carried out using metallic paint sprayed on the steel, with uniform dimensions, mimicking the real paint coatings on the products. The mechanism of $SCCO_2$ treatment was first analysed and specimens treated in different conditions were illustrated. Single-particle shot experiments were afterwards carried out to determine the proper cleaning parameter. The eventual cleaning results using wet shot blasting demonstrated that theoretical analysis was appropriate in this $SCCO_2$ treatment. The resultant cleaning, by use of these two methods, showed satisfactory removal results.

Keywords: *Remanufacturing cleaning; Supercritical CO_2; paint coatings; wet shot blasting*

1. Introduction

Remanufacturing, as an industrial practice, is a specific type of recycling in which the end-of-life/used products are returned to like-new or better performance (Bernard, 2011; Liu et al., 2015a). It offers a new approach to recover the functionality of a product, conserving not only the raw material content, but also much of the value added during the processes required to manufacture new products (Giutini and Gaudette, 2003). Steps such as cleaning, disassembly, inspection, reconditioning, test and reassembly are employed in the remanufacturing process. The end-of-life/used products, denoted as cores (Nnorom and Osibanjo, 2010), go through these steps to attain the original performance level (Abdulrahman et al., 2015; Ijomah, 2009) and be equal to the new product warranty (Ijomah et al., 2007). Among these steps, cleaning is obviously one of the most demanding because it directly influences the quality of the subsequent processes, i.e. surface inspection, reconditioning, reassembly and painting treatment (Li et al., 2015).

Contaminant types vary on different cores, e.g. grease, corrosion, scale, carbon deposition and their mixture(Liu et al., 2013). Basically, the cleaning process during remanufacturing removes these contaminants from the cores to the required cleanliness, by mechanical, physical, chemical or electrochemical methods. Coatings, which are artificially coated on the metal products for protection and nice appearance, are one of the commonly observed substances needed to be removed during the cleaning process. This is because that the coatings affect the defect inspection and the condition of reconditioning, hence, impacting the quality of the remanufactured products.

Product coatings are designed to be robust to survive adverse conditions (Chen et al., 2010). Accordingly, the removal of these coatings is more difficult to achieve than that of the other contaminants. Research of the coating removal using laser method (Chen et al., 2010; Daurelio et al., 1999), ultrasound (Reinhart, 1989), conventional aqueous cleaning methods (Wolbers, 2000), dry-ice cleaning (Spur et al., 1999) and blasting cleaning (Momber, 2007; Raykowski et al., 2001) has been widely studied.

Each method has associated environmental impacts. During laser cleaning, a focused laser beam combusts paint layers; the small dimension of laser restricts the efficiency of the cleaning process Hazardous gases emitted during laser cleaning are also an inevitable environmental issue when large amount of cores are cleaned. Using organic materials or other chemical removal technologies, aqueous cleaning is considered problematic from an environmental perspective, as it involves various forms of more or less hazardous solvents and detergents (Sivakumar et al., 2009). As dry-ice cleaning sublimates into the atmosphere immediately after the cleaning process, its industrial application aggravates the greenhouse effect. There could be much dust pollution during the conventional blasting cleaning (Balan, 2008), which can probably be harmful to the operators. By adding the water into the shot blasting system, the pollution can be significantly reduced.

In addition, for the end-of-life products, there are usually other organic or inorganic mixtures of contaminant of on the surface or the paint layers, making the situation completed. Our previous studies (Li et al., 2015; Liu et al., 2015a; Liu et al., 2015b) have demonstrated that the combination of supercritical carbon dioxide ($SCCO_2$), as a pre-treatment process, and wet shot blasting, as the removing means, has the feasibility of removal oily contaminant on core surface. When these contaminants are on the paint layer, which is commonly observed, the cleaning situation could be different. Considering that the paint is of organic composition, the feasibility of $SCCO_2$ treatment requires study.

In this paper, the feasibility of this environmental sound combination of the two cleaning methods is studied on the paint layers. Coatings are studied without the existence of other type of contaminants; stainless steel specimens are artificially coated with the metallic paints to mimic the real coatings on the remanufacturing cores. Results from the experiment show results consistent with the theoretical analysis of the mechanism of $SCCO_2$ treatment. Single-particle shot experiments and wet shot blasting cleaning were conducted using the specimens from a previous treatment, illustrating that wet shot blasting cleaning is more effective when accompanied by $SCCO_2$ treatment. Although the efficiency of this process is not yet as high as other methods, this combination of the methods provides an approach to cleaning the paint layers which could prove more environmentally friendly.

2. Mechanism of $SCCO_2$ Treatment in Paint Layers

The presence of a critical point of a pure substance was first discovered by Baron Charles Cagniard de la Tour in 1822 (Berche et al., 2009; Cagniard de La Tour, 1822) and Thomas Andrews named this phenomenon as supercritical (Andrews, 1869) in 1869. A supercritical fluid (SCF) is defined as a substance in the status that temperature and pressure are both over its critical point, as illustrated in Figure 1. In terms of CO_2, its critical temperature (Tc) is 304.128 K and critical pressure (Pc) is 7.38 MPa, which is easy to attain under the experiment condition. Currently, the $SCCO_2$ has been widely used for extraction (Lang and Wai, 2001; Marsal et al., 2000; Teberikler, 2001), food processing (Brown et al., 2008; Kinyanjui, 2003), textile processing (Long et al., 2011; Montero et al., 2000), chemical synthesis (Jessop and Leitner), and cleaning as a solvent (Della Porta et al., 2006; Ramachandrarao, 2006).

When a substance is in the supercritical status, there is no phase transaction between vapour and liquid. Properties of the SCF can change continuously between gas-like and liquid-like, so that the supercritical fluid presents the properties of both gas and liquid like, including relatively low viscosity, near zero surface tension, high diffusivity and liquid-like density, allowing it to promote mass transfer. Additionally, the operating conditions of CO_2, as aforementioned, are easily attained and relatively benign and CO_2 is non-toxic and non-flammable. It is thus safe to operate paint layer processing using CO_2 in the supercritical status.

$SCCO_2$ has the low viscosity and extremely low surface tension. Consequently, in the supercritical status, the CO_2 molecules diffuse effortlessly into the internal structure of the paint layers. In a certain period of time, the long-chain organic compounds in the layer become porous. This phenomenon has been widely used in the synthesis of porous materials by researchers (Cooper, 2003; Cooper and Holmes, 1999). The foaming theory, describing the behaviour when an organic substrate contacts an SCF, is one of the widely accepted theories and is the main mechanism utilised in the treatment process in this paper. Many models have been established to explain the foaming phenomenon, of which the bubble nucleation theory is widely used (Frayssinet et al., 1998; Goel and Beckman, 1995). In the supercritical condition, CO_2 molecules diffuse inside the polymeric substance becoming a homogeneous system. During the rapid decompression, CO_2 molecules in this system aggregate as a result of the nucleation, developing a tremendous amount of micro bubbles inside the polymer. These bubbles gradually gather and grow bigger until the swelling force reach equilibrium with the resistance, eventually forming cellular structures in the polymer. The walls between two bubbles bear the tensile stress, which is generated during the bubbles becoming bigger. However, the wall may eventually rupture as a result of the expansion of these bubbles; the bubbles, then join together to form a bigger one, as illustrated in Figure 2.

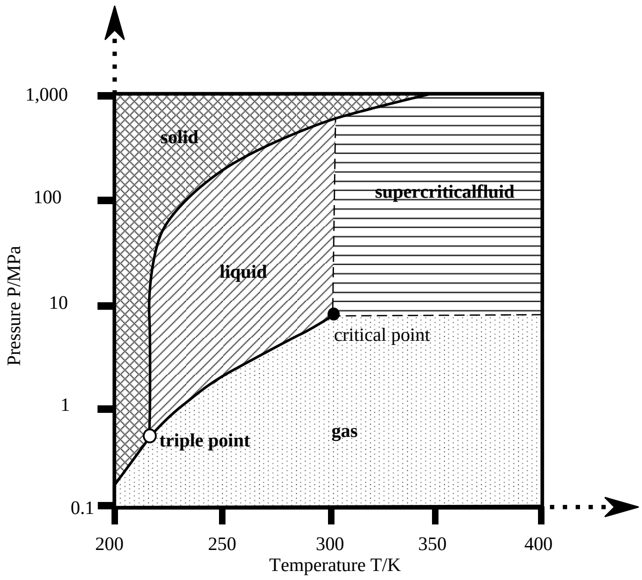


Figure 1 Temperature-pressure phase diagram of carbon dioxide

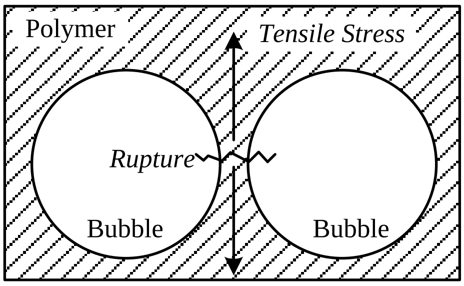


Figure 2 The merger of bubbles and the rupture of the wall

Based on this theory, the treatment using the $SCCO_2$ can be divided into three processes. Firstly, the CO_2 molecules, in a supercritical condition, diffuse into voids within the paint layer, becoming homogeneous phase with the paint. During the rapid decompression process, CO_2 becomes supersaturated in this homogeneous phase and it is decompressed too fast for CO_2 molecules to escape from the layers; clusters of molecules aggregate into micro bubbles in the paint. Eventually, tensile stresses as a result of the pressure difference between the bubbles and the atmosphere ruptures the adjacent walls between adjacent bubbles, generating larger bubbles. Cracks form in different positions in the layers, as depicted in Figure 3, namely interfacial cracks, internal cracks and surface cracks, as the results of bubbles generated in different positions. The generation of the bubbles increases the thickness of the layers and some will split the paint surface.

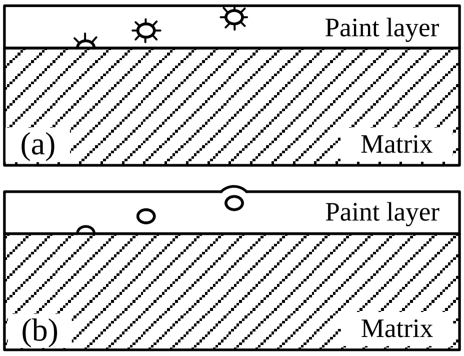


Figure 3 Schematic diagram of crack formation in paint layers

The thermal effect is another notable factor employed in the $SCCO_2$ treatment. The temperature in the supercritical condition is over 40 ℃; thermal expansion acts on both the paint and the matrix. However, the expansion coefficient of the two materials differs and the paint layer is in viscous flow state; consequently, the stress between the two materials is redistributed at this temperature. In this paper, the linear coefficients of thermal expansion for the epoxy paint and stainless steel are 6.0×10^{-5} and 1.01×10^{-5} $℃^{-1}$ respectively. Once the system is quickly decompressed, tensile stress between paint layers and the matrix is formed as a result of the thermal contraction induced by the decreasing temperature. When the stress inside the interface is higher than the strength of the paint layers, there will be channel cracks and transverse cracks emerged on the layer surface.

3. Apparatus, materials and experiment procedures

3.1 Apparatus

Supercritical fluid treatment is implemented in the TC-SFE-50-1-120S laboratory apparatus, manufactured by Suofuer; it has a 1 litre cylindrical vessel designed to operate at pressures up to 50 MPa and temperatures from 15 to 300 ℃. The deviation of temperature in this apparatus can be controlled to ±2 ℃, measured by a thermocouple directly in contact with the fluid in the vessel. The pressure was measured by a piezometer with accuracy of ±0.2 MPa.

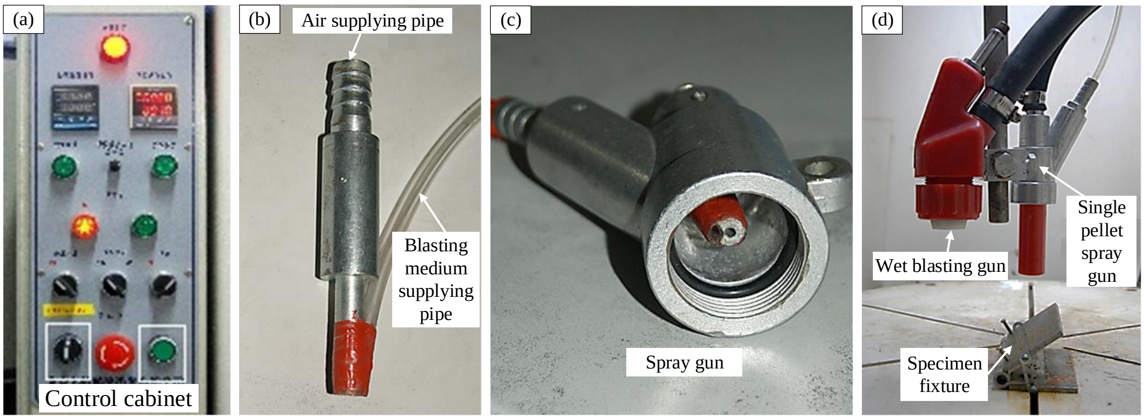


Figure 4 Reconstructed apparatus of the abrasive shot system

Single-particle shot test and wet shot blasting cleaning was carried out on a cleaning equipment. It was modified from the YT0-1308 grit blasting machine manufactured by the Beijing Dotel and FU22A air compressor manufactured by Fusheng. The reconstruction was carried out on the control cabinet, the spray gun and the air supplying pipe. In Figure 4, (a) is the reconstructed control cabinet. Two switches were added, namely function selection button in black and the single particle button in green at the bottom, to achieve the wet blasting and single particle shooting functions in one equipment. The (b) illustrates the change inside the spray gun. Particles inside the hose are siphoned by the compressed air from the pipe next to the hose. The single-particle impact system was regulated at pressure between 0.2 MPa – 1.0 MPa, with ejection system *s*=80 mm long and diameter of 6 mm to ensure the sufficient acceleration of grit particles. (C) is the bottom view of the spray gun and the global view of the reconstructed facility is illustrated in (d), with the specimen fixture that can adjust the spray angle. In this paper, the incident angles, in Figure 5, were all fixed at 90° to study the effect of single particle shot and wet shot blasting on the paint removal.

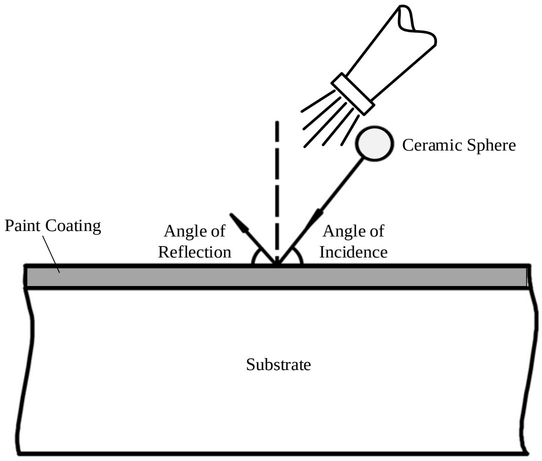


Figure 5 A schematic diagram of the shot blasting cleaning by the reconstructed apparatus

3.2 Materials

In the remanufacturing industry, paint layers are mainly on the surface of cores. It is difficult to obtain identical paint layers with same thickness and performance using these real cores and the dimension of the experimental treatment vessel restricts real components in the process, as well. Consequently, the experiment was carried out using specimens instead to study the parameters involved in the cleaning process. Specimens were 304 stainless steel substrates of size 50×25×2 mm, artificially coated with the epoxy micaceous iron oxide paints. The steels were polished by #400 and #600 sandpapers and measured using the roughness tester to guarantee the roughness deviation of different substrates less than 5%. Steel substrates were then soaked in acetone and cleaned by ultrasound. Spray was applied in a spray booth. The thickness of one spray was 0.02 mm and the final thickness was controlled by the spraying times. After each spray, specimens were left to stand for 20 min before the next application until the expected thickness was achieved; the samples were then naturally dried for 2 months. All the processes above guaranteed the robustness of the paint layers to mimic the actual coatings on the cores.

CO_2 for the supercritical treatment was of 99 % purity.

Table 1 Composition of the ceramic grit

Ingredient	ZrO	SiO	Others
Mass Fraction	68%	31%	1%

Table 2 Physical properties of the ceramic grit

Specific Gravity	Bulk Density	Mohs Hardness	Granularity
3.85	2.36 kg/l	7.7	90%

In this paper, ceramic grit was used as the abrasive media in the wet shot blasting cleaning process. Its chemical composition and some of the physical properties is shown in Table 1 and Table 2. The ceramic material in blasting does not contaminate the component surfaces and the performance after blasting is more stable. Also the density of a ceramic material is relatively low, which consequently lowers the energy consumption of propulsion during the blasting process. It is widely found in industrial use for mould cleaning and oxide scale removal (Litchfield et al., 2006; Tolpygo et al., 2001). Grit was selected individually before the blasting process using callipers to ensure that each particle had similar granularity and dimension; the final grit was shown in Figure 6.

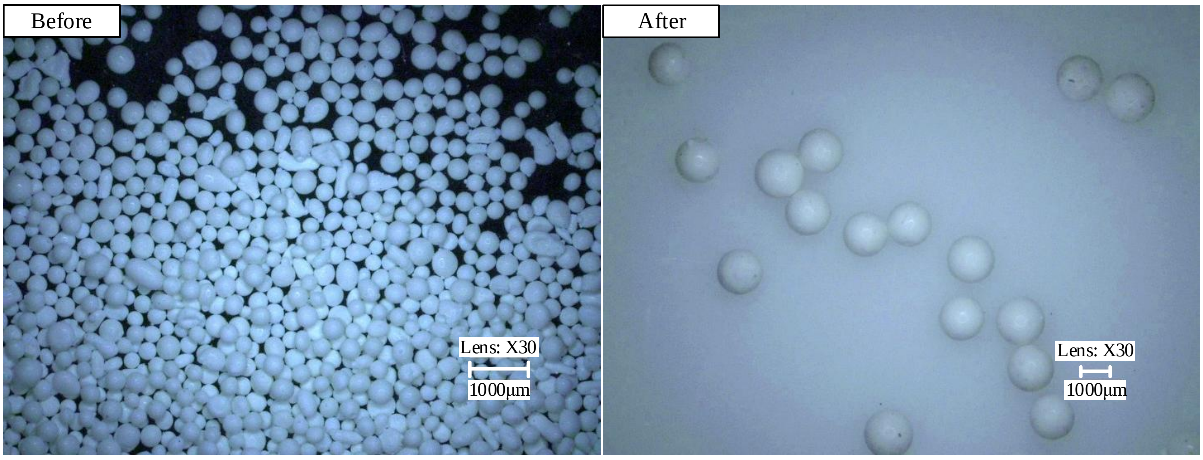


Figure 6 Ceramic grit before and after the selection

3.3 Experimental Procedures

The treatment using $SCCO_2$ was implemented in the vessel of the apparatus, TC-SFE-50-1-120S laboratory apparatus. As depicted in Figure 7, the pressure was raised to a given value and went through the dwell process; after this process, CO_2 was quickly released to the pressure of atmosphere. Morphology of these specimens was inspected by microscopy and ultra-depth microscopy. Table 3 indicates the range parameter employed to investigate the effects, i.e. dwell time, pressure, temperature and the paint thickness, in the $SCCO_2$ treatment process. These specimens treated by $SCCO_2$ were then treated with single-particle blasting experiment and wet shot blasting cleaning to obtain the suitable cleaning parameters in the painting layer removal.

Table 3 Experiment parameters of $SCCO_2$ treatment

Group	Dwell time (h)	Pressure (MPa)	Temperature (℃)	Thickness (mm)
Pilot	0.5	25	40	0.1
1	0/1/2	25	40	0.1
2	0	10/15/25	40	0.1
3	0	15	40/60	0.1
4	0	25	40	0.06/0.1/0.2

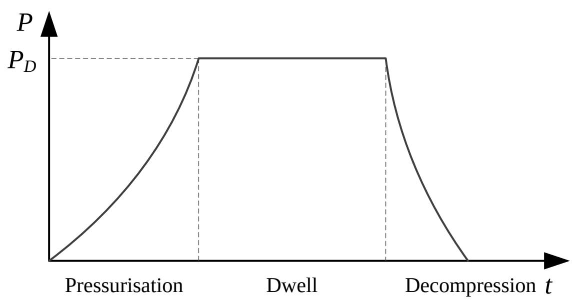


Figure 7 Pressure curve of $SCCO_2$ treatment against time

4. Results and discussions

4.1 Appearance changes by $SCCO_2$

The pilot experiment was designed primarily to study how the $SCCO_2$ affects the morphology of the painting layer. Specimens in this group were coated with 0.1 mm thick paint and placed in treatment vessel in which $SCCO_2$ was afterwards pressurised to 25 MPa and heated to 40 ℃ for 0.5 h. The vessel was afterwards quickly decompressed to the atmospheric pressure and specimens were the taken out for inspections. The treated specimens were compared with the originally smooth appearance. As illustrated in Figure 8, there was no distinct change right after the specimen was taken out. However, after being exposed to the atmosphere for 1 min, white substances emerged on the layer surface though the layer itself had no distinct changes. The white substance was the vapour desublimation as a result of specimens rapid cooling down by the decompression. After 2 min, the paint layer began to swell and was covered by more white substances, which was proved to be ice crystals. These crystals vanished in 3 min after the exposure and a bubble-like appearance was observed accompanied with cracking sounds. The cracking sounds were due to the fracture of paint layers as a result of swelling and tension stress inside.

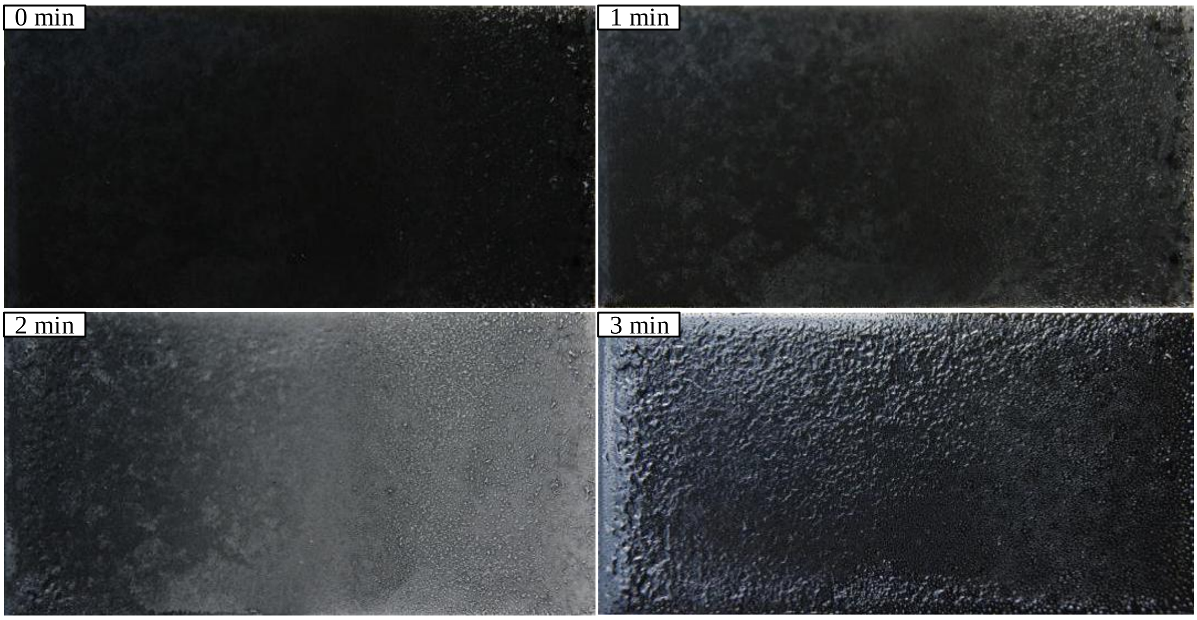


Figure 8 Specimen appearance change against time when exposed to the atmosphere

The other four groups of experiment were designed to study the effects of different parameters on treatment, namely dwell time, pressure, temperature and the layer thickness. Representative outcomes of specimens under different conditions are illustrated in Figure 9. Apparent channel cracks and transverse cracks emerged and swelling developed in the centre of the pieces fragmented by these cracks when the vessel was immediately decompressed without dwelling. However, when the dwell time was 1 h or 2 h, there were not apparent cracks and the thickness of the swelled pieces increased with the surface becoming uneven. This can be similarly observed in Figure 8 (3 min), in which the specimen was soaked in the pressurised vessel for 0.5 h.

When there is no dwell time employed in the treatment, very few CO_2 molecules diffuse into the paint layers. The small amount of CO_2 molecules cannot resist the tensile and shear strength from the thermal contraction induced by the declined temperature after the decompression; consequently, the paint layer ruptures and cracks are developed on the specimen surface. When the dwell time is increased to 1 h, there can been enough time for CO_2 molecules to form stable structures inside the paint layer. The cellular structure has sufficient elasticity to overcome the thermal contraction; this mechanism is also responsible for the observed results of dwell time 2 h.

When the pressure varied, only the specimen at pressure of 25 MPa had apparent channel and transverse cracks formed (Figure 9-I). Those cracks separated the paint layer into small fragments of a swelled structure. However, at 15 MPa, the cracks generated were not sufficient to form the fragments like those at 25 MPa. It was not even able to generate any cracks when at 10 MPa (Figure 9-II). This is because that there was insufficient dwelling time for CO_2 expansion inside the paint layer to form the cellular structure aforementioned; consequently, when the system was decompressed sharply, the high tensile and shear strength inside the paint layer induced more significant cracks and swelling.

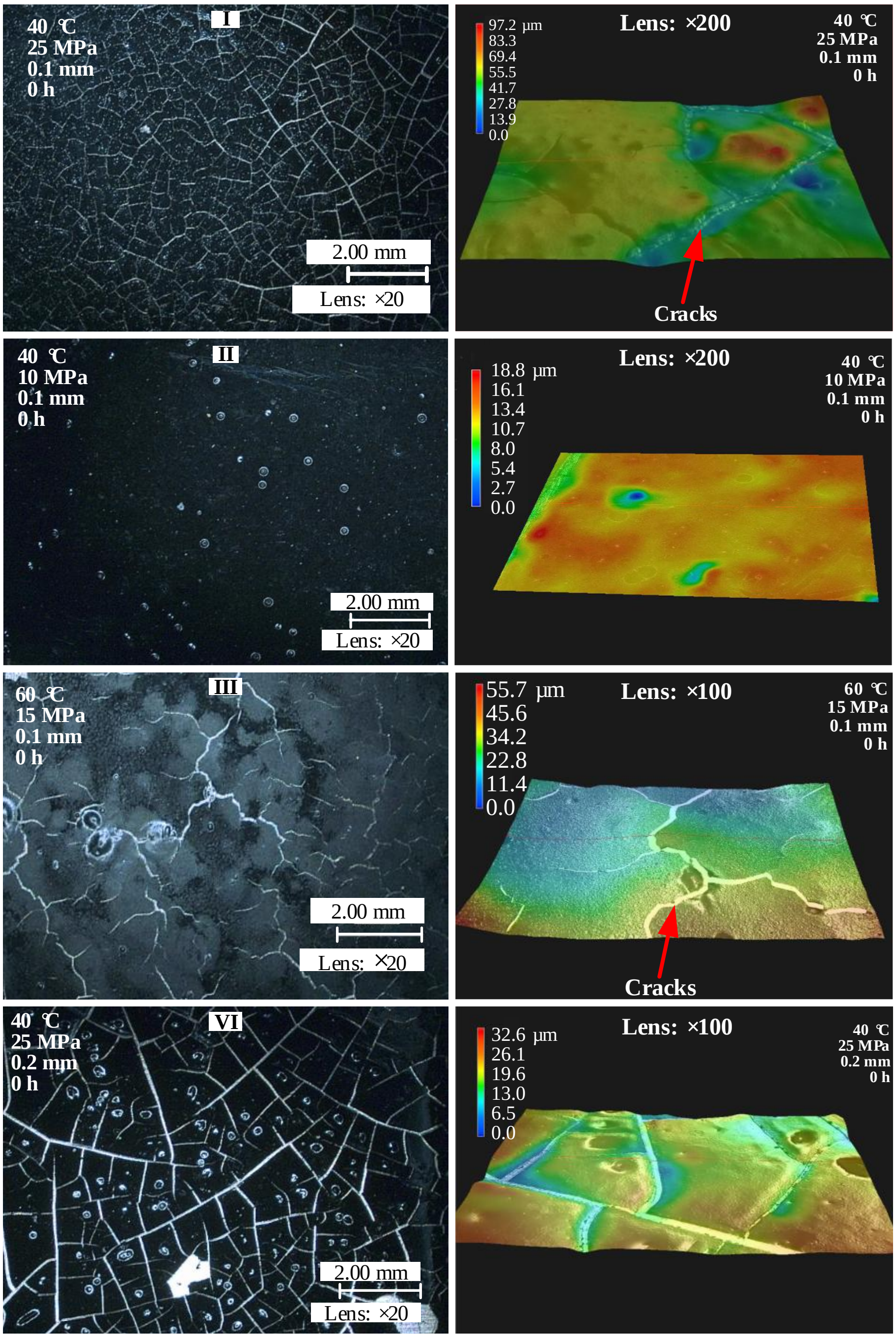


Figure 9 Representative images and morphologies of paint layers under different conditions
I: 40 ℃, 25 MPa, 0.1 mm, 0 h; II: 40 ℃, 10 MPa, 0.1 mm, 0 h;
III: 60 ℃, 15 MPa, 0.1 mm, 0 h; IV: 40 ℃, 25 MPa, 0.2 mm, 0 h;

After the treatment at temperatures of both 40 ℃ and 60 ℃, cracks could be observed on the surface of the specimens, according to the result depicted in Figure 9-III. At the higher temperature, paint layers swelled more significantly due to thermal expansion, leading to a greater volume. Assuming that the specimens were cooled down to 20 ℃ from 40 and 60 ℃, the displacements of paint were calculated to be 0.10 mm/m and 0.20 mm/m, respectively, as thermal contractions. The tensile and shear force inside the layers was greater as the result of a higher temperature difference. Therefore, the cracks were much wider at the higher temperature, but the fragments swelled less seriously.

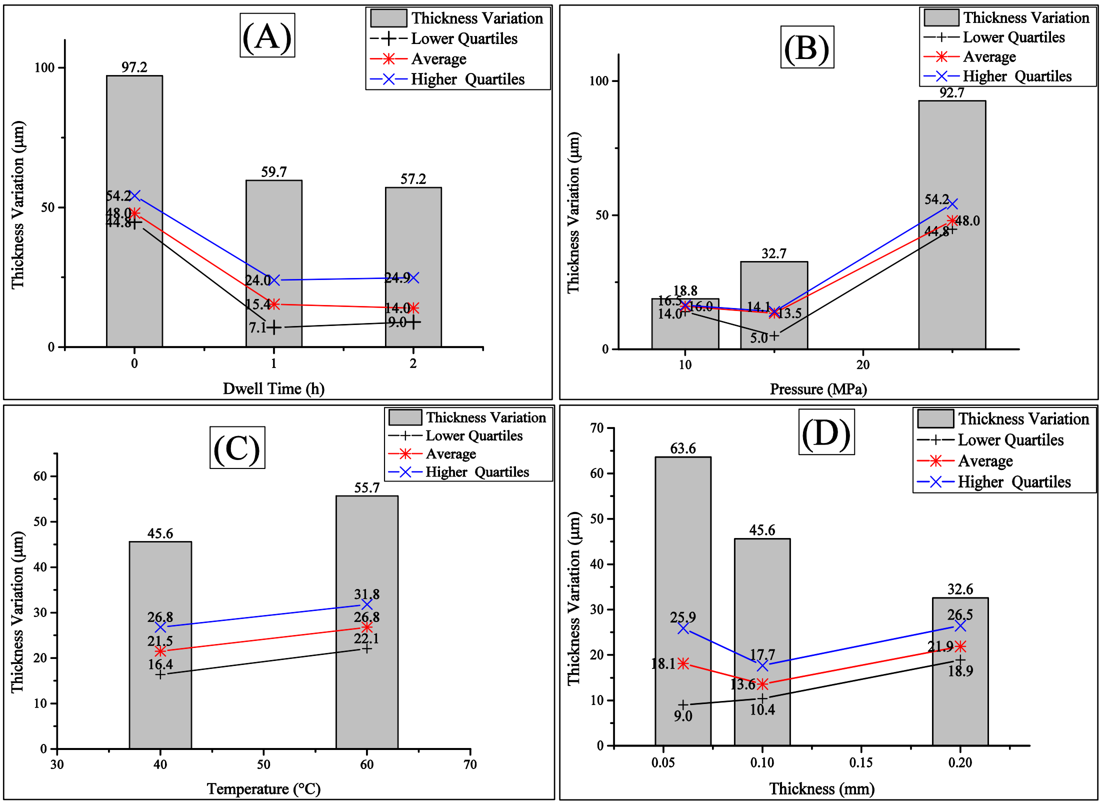


Figure 10 Thickness Fluctuation of paints through different dwell time (A), pressure (B), temperature (C) and layer thickness (D)

The paint thickness is not a decisive factor for the generation of cracks during the supercritical treatment, concluded from the tests with different thickness. At suitable temperature and pressure, the dimension of the cracks and the size of the paint fragments increased with the paint layer thickness (Figure 9-IV). However, the thick paint did not swell significantly as the thinner ones, because the thick paint layer had the capacity to absorb more CO_2 molecules and to distribute the molecules more uniformly.

Figure 10 illustrates paint height, average thickness and height of the lower and higher quartiles of the pixels in each image taken by ultra-depth microscopy and the image data were analysed and collected by image processing software. In these figures, when the average height much lower than the half of the total height, the swelled paint represents very sharp morphology, being proved by the right image in Figure 9 (I). On the contrary, the paint that swelled shows as relatively blunt morphology, as illustrated in Figure 9 (IV). Similarly, when the higher quartile is closed to the top the total height variation, the paint demonstrates sharper swelling; when the lower quartile is closed to the bottom, i.e. zero µm, it can be considered that great proportion of the paint did not swell and still adhered to the substrate materials. By contrast, when the quartiles are closed to the average height, it means that the a large area of the paint has swelled, leading to easier removal from the substrates. In (A), the specimens with one or two hours dwell time shows the similar height distribution, indicating that the cellular structures inside had thoroughly formed. However, it has a negative effect on the generation of cracks, consequently impeding the removal of paint, which will be demonstrated in the following section. The height of paint increased with the pressure (B) and temperature (C), while declines with the increasing thickness. In the experiment range, the pressure and temperature had the positive effect in the generation of cracks while dwell time was a negative factor and the thickness was not the decisive reason when the other parameters were suitable for the $SCCO_2$ treatment.

4.2 Single-Particle Shot

Table 4 Treatment condition of specimens in each group

Group	Pressure (MPa)	Temperature (℃)	Dwell time (h)	Thickness (mm)
a	15	40	0	0.2
b	15	40	0	0.1
c	15	40	0	0.06
d	25	40	0	0.1
e	15	60	0	0.1
f	10	40	0	0.1
g	25	40	1	0.1
h	25	40	2	0.1

Specimens in this test were grouped in Table 4. As it has been demonstrated that cracks were generated on the paint after an $SCCO_2$ treatment, intuitively obvious that it can be easier to remove the paint from the metal matrix. In this section, the experiments were designed to test the effect of propelling pressure and particle dimension on the removal productivity. Tests were carried out at the pressure of 0.2 MPa and 0.4 MPa, and 0.3 mm and 0.9 mm ceramic particles separately, using the specimens from the previous treatment process. In the single pellet spray gun, particles were accelerated by the compressed air. The velocity of the particles impacting on the specimens can be calculated roughly based on

$$F \cdot s = \frac{1}{2} m v^2 \tag{1}$$

where F is the force acting on a particle.

$$F = P \cdot \frac{\pi}{4} d^2 \tag{2}$$

The mass of a particle is

$$m = \rho \cdot \frac{\pi}{6} d^3 \tag{3}$$

Substituting Eqs.(2) and (3) into Eq. (1), it can be obtained that the velocity of the particle shooting out the spray gun is

$$v = \sqrt{\frac{3P \cdot s}{\rho d}} \tag{4}$$

where P is the pressure of the compressed air; s is the length of the spray gun via which the particle is accelerated; ρ is the bulk density of a ceramic sphere and d is the diameter of one particle. Under different pressures, the velocity in the single-particle shot experiment was calculated as $v_{1,1}$=82.3 m/s, $v_{1,2}$=47.5 m/s, $v_{2,1}$=116.4 m/s and $v_{2,2}$=67.2 m/s. Subscriptions represent the low and high level of the accelerating pressure and particle diameters, respectively. The removed areas were analysed by the image processing software ImageJ 1.48 by National Institutes of Health™. As the appearances in each group are similar under test parameters, the results taken by microscopy are selectively shown in Figure 11. Evident removal had been achieved on the surface of those specimens with cracks (a–e). The removed sizes in these groups are compared in Figure 12, which illustrates the result of group from (a) to (e). The area of removed layers increased when the propelling pressure or the shooting grit diameter was higher. However, in the circumstance of using higher propelling pressure (0.4 MPa), there was damage on the matrix as a result of great impact velocity. The test of using 0.4 MPa pressure and 0.9 mm grit was omitted as the damage on the matrix was an inevitable factor that should be taken into consideration when choosing the suitable cleaning condition. The best removal effect was achieved when using the higher propelling pressure and bigger blasting particles.

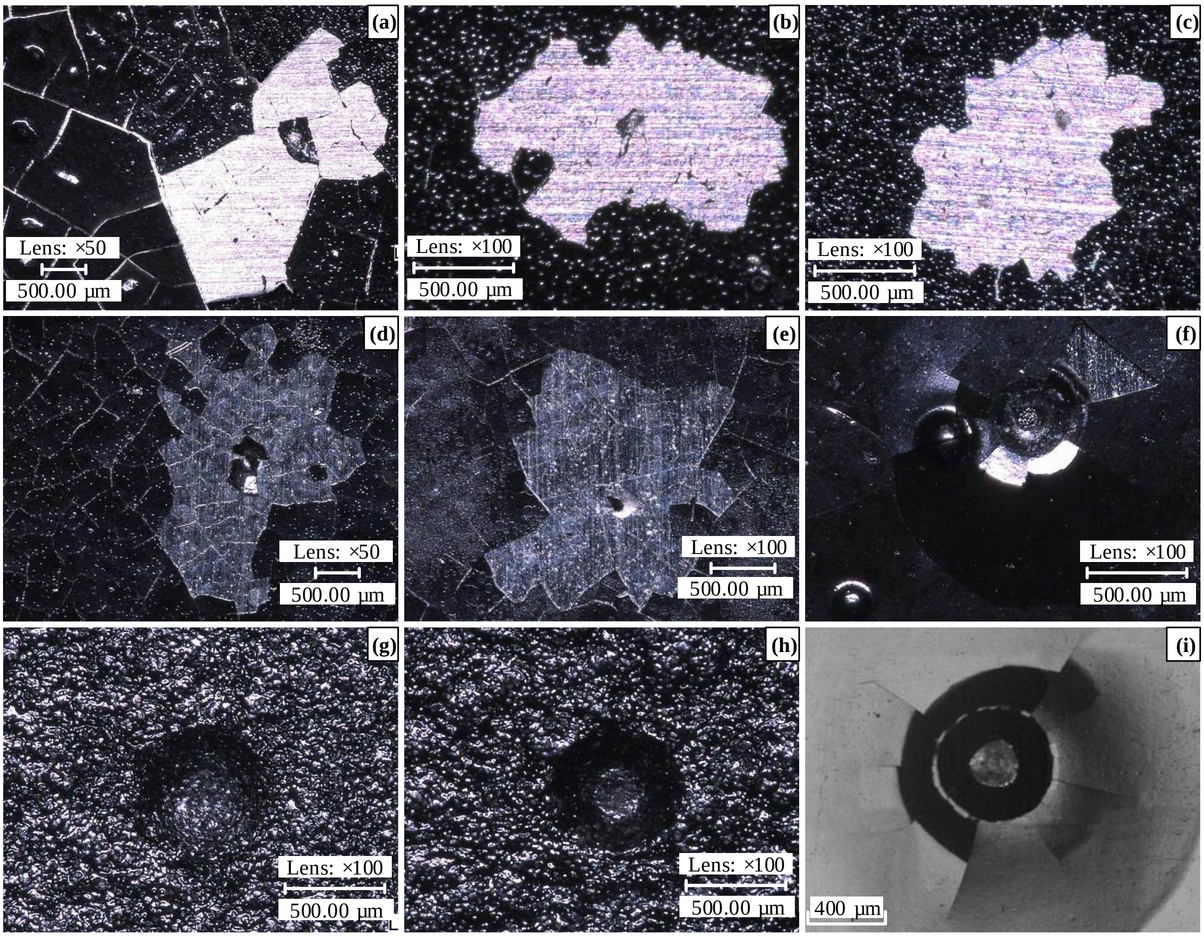


Figure 11 Surface morphology of the specimen after single-particle shot under different treatment conditions according to Table 4

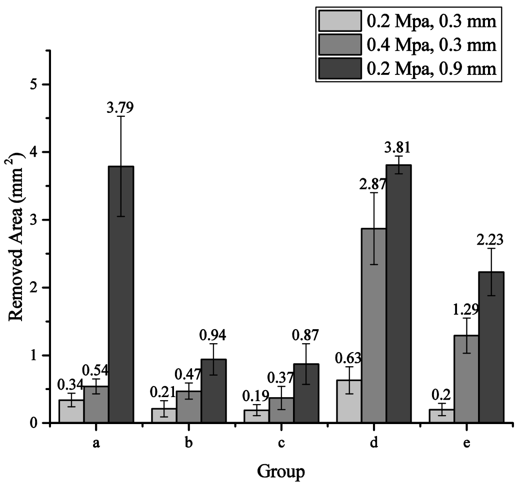
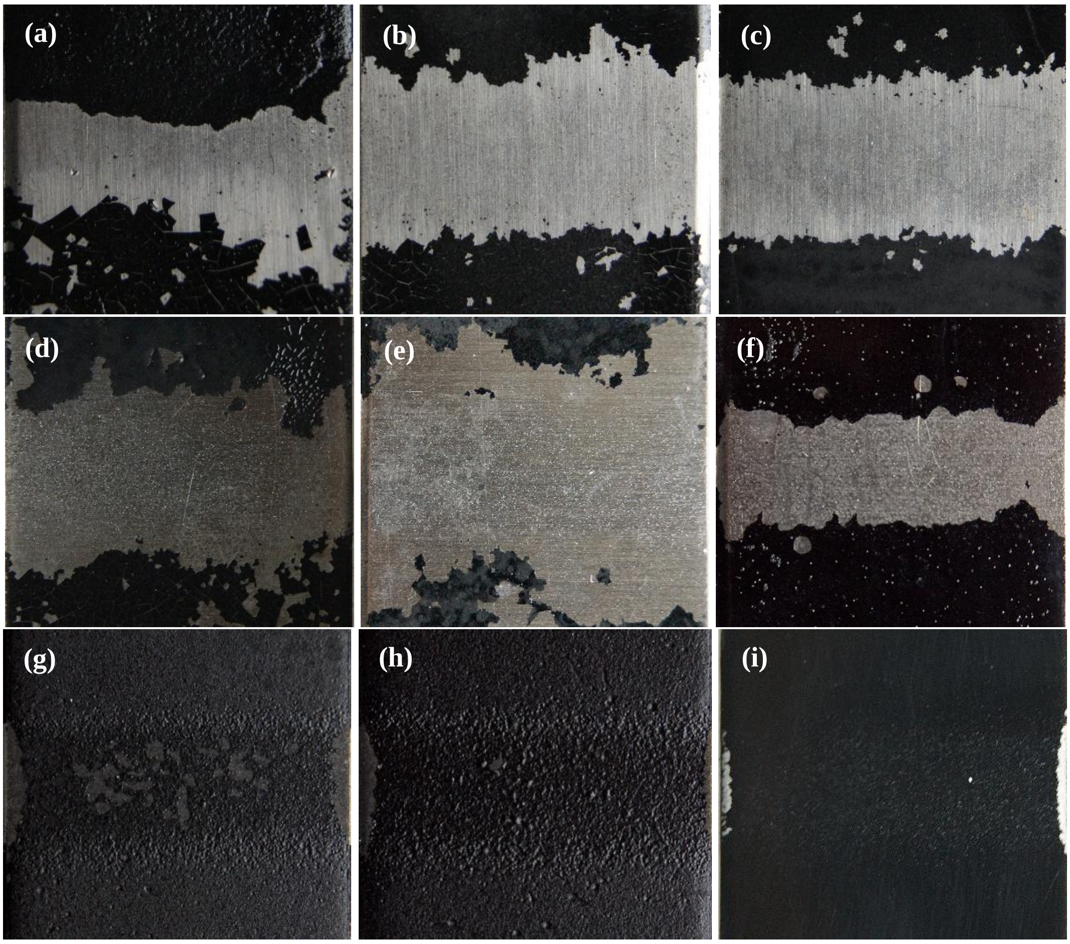


Figure 12 Removed area by single-particle shot test under different impact conditions

Comparing groups a, b and c, it can be concluded that removal productivity increased on the thicker paint. Specimens in group f, whose treatment pressure was low, retained the similar morphology with the specimen in Figure 11 (i) not being treated in $SCCO_2$. The impact-induced coating morphology in these two groups were due to the indentation and the buckling delamination (Evans and Hutchinson, 1984) during the shot process. In the condition that the treatment pressure and temperature were higher, more paint fragments were removed by single-particle shot. The removal effect in group d was apparently better than that in group g and h, which means that it was easier to remove the paint layer if no dwell time was employed in the treatment process. Figure 11 (g) and (h) shows the cellular structures of the specimens with dwelling treatment. The cellular buffered the impact by the blasting shot particles; in the meanwhile, the stress from the shooting grit was effectively distracted. Consequently no crack or removal was found on the surface of specimens in this group.

4.3 Wet shot blasting cleaning

Based on the study of the single-particle study, experiment used the grit with the diameter of 0.75 mm propelled by the pressure of 0.3 MPa for the wet shot blasting cleaning. The 0.6 mm nozzle of the blasting apparatus moved in the velocity of 7×10^{-3} m/s, spraying the wet shot blasting from 50 mm away to the specimens. Specimens with or without the $SCCO_2$ treatment were blasted from one end to the other, by the wet shot blasting with the solid/liquid volume ratio of 1:16.



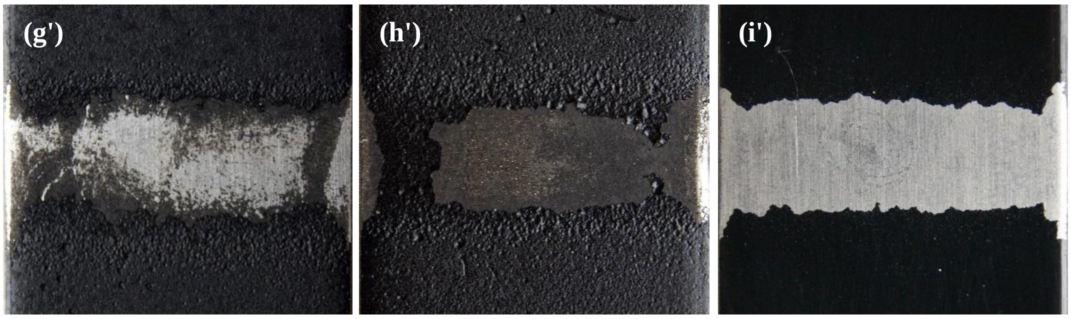


Figure 13 Wet shot blasting cleaning results of the specimens under different parameters in Table 4

As illustrated in Figure 13, the single cleaning process could remove the majority of paint on the specimens (a) – (e), while specimens of (g), (h) and (i) had not been cleaned effectively. The removal percentage, analysed by *ImageJ 1.48*, is depicted in Figure 14. Although wet shot blasting had removed some of the upper level of the paint in (g), (h) and (h'), there were obviously residuals on the so-called cleaned area. Accordingly, the analysis of this three specimens was omitted and the cleaning operation in these groups are considered as failure. The amount of paint removed were similar independent of paint thickness. Better cleaning productivity was achieved when the treatment pressure and temperature were higher, e.g. specimen (e). The cellular structure on those through the dwell process (g) and (h) has reduced with roughly no removal effect. The result proved that there were bubbles inside the paint layers when specimens were soaked in $SCCO_2$ for an excessively long time. The last three specimens were cleaned an additional two times, as (g'), (h') and (i'). The paint layer (i) without $SCCO_2$ treatment was removed in large percentage, while the former two retained massive paint dots residues. Consequently, it has been deduced that dwelling time has a negative effect on effectiveness of wet shot blasting.

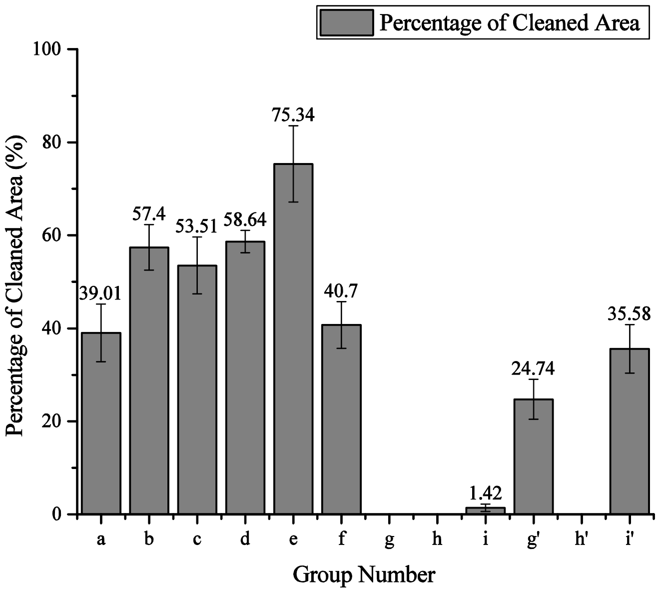


Figure 14 The percentage of cleaned areas in each specimen

5. Conclusions

Traditional cleaning methods, e.g. laser cleaning and aqueous cleaning, used in the remanufacturing cleaning of paint layers, are commonly some of the most environmentally unfriendly, and present an urgent problem to be solved in sustainable manufacturing, with a huge amount of water or conventional chemical cleaning agent being consumed or harmful gases exhausted. A new approach to cleaning the coatings on surface of the cores in remanufacturing is introduced, using $SCCO_2$ treatment and the successive wet shot blasting cleaning. Main mechanisms of $SCCO_2$ treatment have been described using bubble nucleation theory and the thermal effect. Experiments have been carried out using specimens which mimic the real retired parts from the end-of-life products, and results are consistent with the theoretical analysis.

In the work demonstrated in this paper, $SCCO_2$ has been employed as a pre-treatment method prior to the wet shot blasting cleaning, based on the cleaning of specimens mimicking the real paint layers on the remanufacturing cores. Different treatment parameters have been studied through the treatment process and single-particle shot experiments. After this, the wet shot blasting has been used to clean the test specimens from the former process and specific cleaning parameters are selected based on the single-particle shot test. The visible cleaning results showed that:

(1) The temperature effects, bubble nucleation and swelling effects dominate the mechanism of treatment process using $SCCO_2$.
(2) Dwelling time in the treatment process hinders the formation of channel cracks and transverse cracks; cracks can be only formed when the pressure reaches a certain value and the dimension of the cracks increases when the pressure is higher. Fragments segmented by the cracks are lager with increasing treatment temperature and with paint layer thickness.
(3) Even when the impacting velocity is relatively low, paint layers were removed by the blasting; increasing the impacting velocity or the diameter of the grit benefits the cleaning process but higher velocities may also damage the surface of the stainless steel.
(4) The combination of $SCCO_2$ and wet shot blasting cleaning promoted the productivity of the cleaning process; removal results were enhanced when treatment pressure or temperature was higher; specimens with thicker paint layers were cleaned most effectively.

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