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DOI

[10.1021/acsami.7b00638](https://doi.org/10.1021/acsami.7b00638)

Publication date

2017

Document Version

Accepted author manuscript

Published in

ACS Applied Materials and Interfaces

Citation (APA)

Morsch, S., Van Driel, B. A., van den Berg, K. J., & Dik, J. (2017). Investigating the photocatalytic degradation of oil paint using ATR-IR and AFM-IR. *ACS Applied Materials and Interfaces*, 9(11), 10169-10179. <https://doi.org/10.1021/acsami.7b00638>

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ACS Appl. Mater. Interfaces, **Just Accepted Manuscript** • DOI: 10.1021/acsami.7b00638 • Publication Date (Web): 03 Mar 2017

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Investigating the Photocatalytic Degradation of Oil Paint using ATR-IR and AFM-IR

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ABSTRACT

As linseed oil has a longstanding and continuing history of use as a binder in artistic paints, developing an understanding of its degradation mechanism is critical to conservation efforts. At present, little can be done to detect the early stages of oil paint deterioration due to the complex chemical composition of degrading paints. In this work, we use advanced infrared analysis techniques to investigate the UV-induced deterioration of model linseed oil paints in detail. Sub-diffraction limit infrared analysis (AFM-IR) is applied to identify and map accelerated degradation in the presence of two different grades of titanium white pigment particles (rutile or anatase TiO_2). Differentiation between the degradation of these two formulations demonstrates the sensitivity of this approach. The identification of characteristic peaks and transient species residing at the paint surface allows infrared absorbance peaks related to degradation deeper in the film to be extricated from conventional ATR-FTIR spectra, potentially opening up a new approach to degradation monitoring.

KEYWORDS: Linseed oil; titanium white; photocatalytic degradation; FTIR; AFM-IR.

Introduction

Linseed oils have been used as a medium for oil paintings since medieval times, owing to their capacity to form reasonably stable, continuous films with good optical and mechanical properties. Nonetheless, paints made from these and other drying oils are susceptible to long-term degradation, leading to e.g. undesirable changes in optical appearance^{1,2}. For conservation purposes, an in-depth understanding of these degradation mechanisms is necessary to design effective detection and prevention strategies. However, in common with other drying oils, defining the degradation process is notoriously problematic, since linseed oils are complex mixtures of naturally-derived triglyceride molecules based on fatty acids (primarily linolenic, linoleic, oleic, stearic and palmitic acids, with concentrations dependent on the source), Scheme 1. Numerous competing radical reactions drive cross-linking and chain scission, and furthermore, these processes can occur simultaneously. Therefore, no clear distinction can be made between drying and aging.^{3,4,5,6}

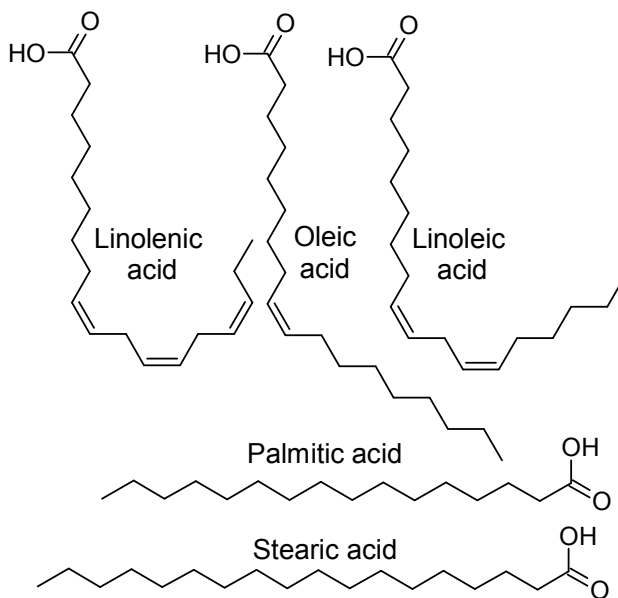
A general mechanism for linseed oil hardening has nonetheless been established; it is widely accepted that oxidative curing is initiated by hydrogen abstraction from methylene groups adjacent to fatty acid *cis* alkenes (since the unsaturated bonds stabilise generated radicals by conjugation), Schemes 1 and 2. Oxygen sorption then results in the formation of highly reactive peroxy radicals, followed by a variety of radical coupling reactions that ultimately lead to cross-linking.⁷ At the same time, chain-scission reactions are initiated by further radical formation (via e.g., β -scission reactions). Furthermore, in artists paint the complexity of this process is compounded by interaction with the inorganic pigments, which can affect both the drying process and the degradation kinetics. For example, pigments behaving as Lewis acids or bases locally induce metal salt or soap formation and may accelerate hydrolysis,^{8,9,10,11,12,13,14} whereas photocatalytic pigments, such as titanium white, can induce additional radical formation.^{15,16}

Titanium white pigments were introduced in the beginning of the 20th century, and paints containing these pigments have been used in many renowned artworks produced since (e.g., paintings by Picasso, Mondrian, and Pollock). These prevalent pigments occur in numerous forms, including the pure anatase and rutile polymorphs, with or without surface coatings. As a result, photocatalytic activity varies drastically. Generally, pure anatase exhibits the highest photocatalytic activity while rutile is considered more benign, and surface coatings further reduce activity^{17,18}. Upon UV absorption, photocatalytic pigments provide reactive electrons at the surface of

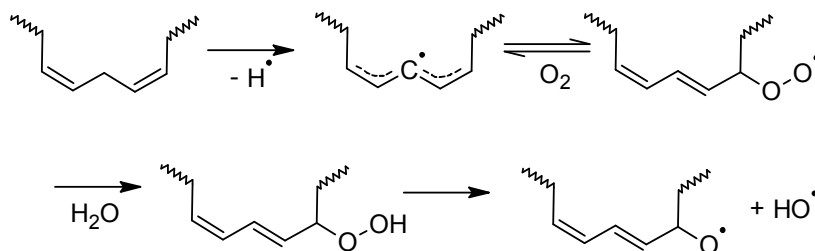
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3 particles, resulting in the formation of organic radical and reactive oxygen species.
4 For binders that cure by radical polymerization (e.g., linseed oil), the presence of
5 photocatalytic pigments is therefore expected to accelerate crosslinking, and this
6 may result in embrittlement. Concurrent degradation processes are also expected to
7 initiate, and these ultimately manifest as chalking, where pigment powders are
8 exposed at the paint surface after the binder has been broken down into volatile low
9 molecular weight species^{16,19}. Valuable works of art containing titanium dioxide are
10 relatively recent and often stored under controlled conditions, therefore these long-
11 term degradation effects are rarely observed²⁰. Nonetheless, understanding the
12 degradation mechanism is key to the development of prophylactic conservation
13 strategies. It has recently been reported that uncoated anatase pigments dramatically
14 accelerate UV-induced degradation of linseed oil when compared to coated rutile
15 pigments. Surface sensitive techniques (AFM, XPS) were used to prove that the
16 pigments were rapidly exposed at the paint surface, and that this was followed by
17 visible chalking. However, little information about the binder degradation mechanism
18 is provided by these techniques.¹⁶

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28 One approach to polymeric analysis, infrared spectroscopy, can provide
29 detailed information about the presence and chemical environment of functional
30 groups, and has previously been used to investigate the drying and aging
31 mechanisms of oil paints.^{7,11,21} However, conventional FTIR analysis is ordinarily
32 confined to bulk measurements, where lateral resolution is restricted by the beam
33 spot size and the penetration depth is dependent on the collection mode. Bulk
34 spectra therefore represent an average of all chemical changes occurring within this
35 sampling space. In contrast, the early stages of pigment-induced degradation are
36 expected to be heterogeneous, involving highly localised chemical changes. To
37 overcome this, FTIR microspectroscopy has previously been used to map aged paint
38 samples. For example, Boon et al have mapped lead soap aggregate in cross-
39 sections of aged paints,^{22,23,24} and Mazzeo et al applied the same technique to map
40 metal soap formation in reconstructed paint films.¹² Whilst this methodology allows
41 the chemical differences between layers of paint to be resolved post-degradation,
42 infrared microspectroscopy techniques conventionally suffer diffraction-limited
43 resolution associated with the wavelength of light in the mid-IR spectral range, and
44 are typically restricted to several microns per pixel.²⁵ In contrast, the recently
45 developed AFM-IR technique circumvents these limitations by using an AFM probe to
46 detect local photothermal expansion in response to infrared excitation, routinely
47 providing local spectra and infrared mapping with lateral resolution <50 nm.²⁶ AFM-IR
48 has previously been applied to map chemical heterogeneity and water transport
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3 within an unpigmented epoxy-phenolic lacquer.^{27,28,29} In this study, we extend this
4 approach to a model linseed oil paint containing titanium dioxide pigments, and apply
5 ATR-FTIR alongside AFM-IR to identify and map the infrared peaks associated with
6 photocatalytic degradation.
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31
32 Scheme 1. Chemical structures of major fatty acid components of triglyceride molecules in
33 linseed oil.



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47 Scheme 2. Proposed mechanism of hydroperoxidation of linoleic acid.
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Experimental

Sample Preparation

Model paints with a pigment volume concentration (PVC) of 15% were prepared by mixing commercially available titanium dioxide (either Hombitan LW uncoated anatase by Sachtleben Chemie or Tronox CR-826 coated rutile by Tronox), bleached commercial linseed oil (van Beek, NL, used without further treatment), and 0.1% v/v drying agent (cobalt and zirconium carboxylates, Pieter Keune, NL). All reagents were used as received. After milling, paint was applied onto Melinex supports using a draw down bar coater, (nominal thickness of 100 μm), and left to dry for 14 days under ambient conditions ($T = 20\text{ }^{\circ}\text{C}$, cyclic lighting). Samples were aged in an Opsytec Dr. Gröbel BS-02 UV chamber equipped with UVA lamps (i.e., broad irradiation at wavelengths between 300 nm - 400 nm) and removed periodically. The received UV dose was continuously monitored by a UVA sensor inside the chamber, and then the sample location was corrected for in accordance with the manufacturer's specifications, Table 1. After removal from the UV-chamber, samples were stored under ambient conditions in the dark prior to analysis.

Table 1: UV doses received by coated anatase and uncoated rutile pigmented linseed oil paint samples.

Irradiation Step	UV Dose / J cm^{-2}	
	Anatase	Rutile
Dried&stored	0	0
1	2.1×10^3	1.9×10^3
2	4.2×10^3	3.8×10^3
3	5.4×10^3	4.7×10^3
4*	6.3×10^3	6.3×10^3
5*	7.3×10^3	7.2×10^3

**local chalking is observed by eye for anatase paint samples*

ATR-FTIR

Bulk infrared spectra were obtained from the paint surface from 16 co-averaged scans collected in ATR mode using an FTIR spectrometer (Perkin Elmer Spectrum 1000 FT-IR) operating at 1 cm^{-1} resolution across the $450\text{--}4000\text{ cm}^{-1}$ range, with a Graseby Specac Golden Gate Single Reflection Diamond ATR. The penetration

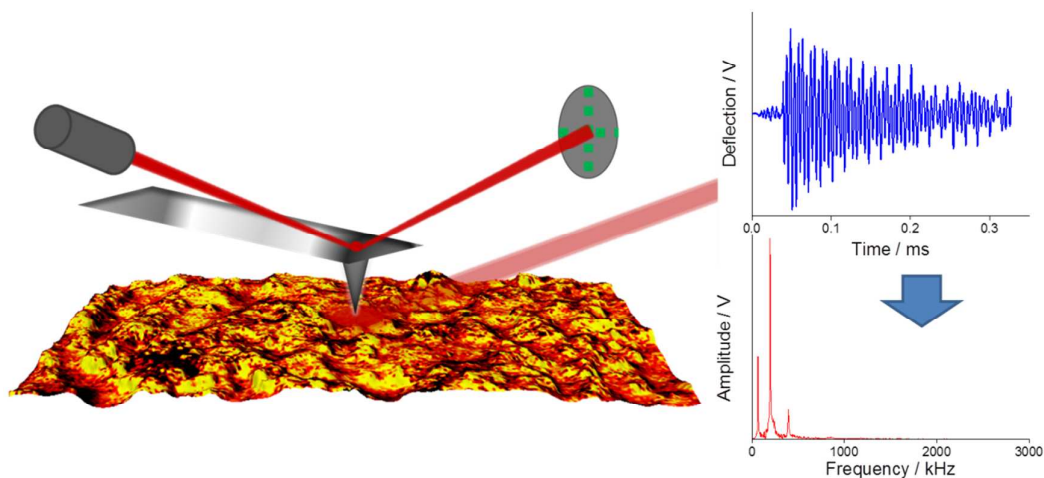
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3 depth of the evanescent wave generated at a diamond internal reflection element is
4 estimated to be $\sim 2 \mu\text{m}$ in the mid-IR range. Spectra were collected from five different
5 locations on each sample.
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8 9 AFM-IR

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11 Nanoscale infrared analysis (AFM-IR) was performed on a NanoIR2 system (Anasys
12 Instruments) operating with top-down illumination. During AFM-IR analysis,
13 specimens were illuminated by a pulsed, tuneable infrared source (optical parametric
14 oscillator, 10 ns pulses at a repetition rate of 1 kHz, approximate beam spot size 30
15 μm). Sub-diffraction limit resolution is achieved by monitoring the deflection of an
16 AFM probe, which responds to rapid infrared-induced thermal expansions of the
17 sample in contact with the probe tip, Scheme 3. The recorded AFM-IR signal is the
18 amplitude of induced AFM probe oscillation, obtained after fast Fourier transform.
19 This has previously been shown to correlate to infrared absorbance measured using
20 conventional macroscopic FTIR.³⁰ Furthermore, since the IR pulse (10 ns duration),
21 thermal expansion, and damping down of the induced oscillation occur on a shorter
22 timescale than the feedback electronics of the AFM, simultaneous contact-mode
23 topographical measurement and infrared mapping can be performed at a given
24 wavelength.^{31,32,33,34} For the present study, AFM-IR images were collected in contact
25 mode at a scan rate of 0.1 Hz using a gold-coated silicon nitride probe (0.07 – 0.4
26 N/m spring constant, 13 ± 4 kHz resonant frequency, Anasys Instruments). The
27 amplitude of infrared induced oscillations were recorded at a given wavelength using
28 16 co-averages for 600 points per 150 scan lines. Spectra were obtained at a single
29 position using 1024 co-averages for each data point. Infrared ratio images were
30 generated using AnalysisStudio software (v3.8, Anasys Instruments) by division of
31 the overlapping regions of IR amplitude maps, cross-correlated using the
32 corresponding height images. For cross-section analysis, samples were cut using a
33 scalpel and then immediately mounted at 90° in a sample holder (model SD-103,
34 Bruker) and imaged.
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52 Scanning electron microscopy images were obtained using an FEI Quanta 650 field
53 emission gun scanning electron microscope operating in low vacuum mode using an
54 accelerating voltage of 10kV.
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Scheme 3. The AFM-IR experiment with top-down illumination. The IR source is pulsed, inducing rapid thermal expansion of the sample, which is detected by deflection of the AFM probe cantilever. The recorded AFM-IR signal is the amplitude following a fast Fourier transform of the deflection signal.

Results

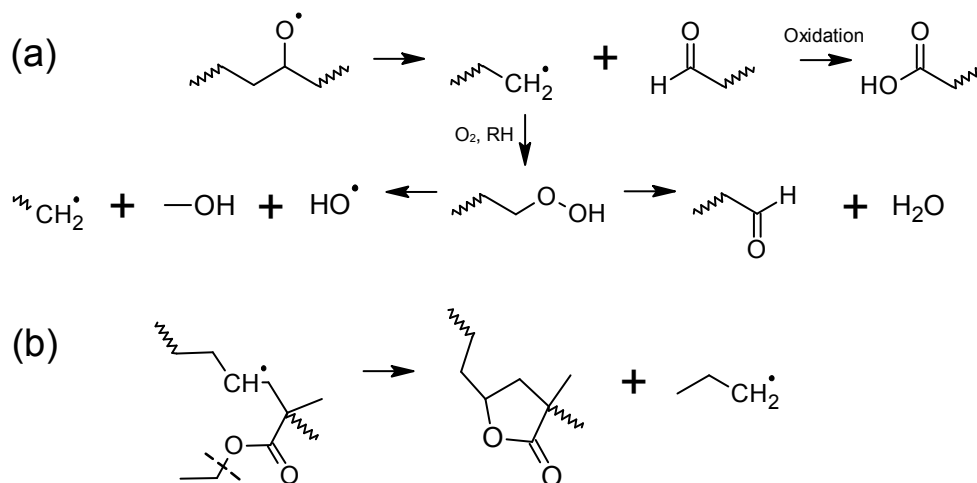
ATR-FTIR

Before AFM-IR analysis, specimens were investigated using bulk ATR-FTIR, Figure 1. All samples displayed absorbance peaks characteristic of linseed oil, summarised in Table 2. Prior to UV aging, the absence of a characteristic *cis* =C-H stretch absorbance at 3010 cm^{-1} indicated that oxidation of the *cis* unsaturated groups had taken place during drying and storage under ambient conditions. This is in keeping with findings detailed by Lazzari et al, who found that for unpigmented linseed oil, absorption associated with the fatty acid *cis* alkene groups disappeared within 8 hours drying time.⁷ The dried linseed oil spectra show typically broad carbonyl and hydroxyl absorbance peaks; this is because the alkoxy and peroxy radicals formed by oxidation of the *cis* unsaturated groups (Scheme 2) react further during drying, generating a variety of functional groups including ethers, esters, acids, alcohols, aldehyde and ketone species. Natural maturing/degradation then occurs as a result of further oxygen sorption and (less favourable) organic radical formation in a continuation of the same process. The resulting complex mixture of functional groups yields characteristically broad overlapping infrared absorbance peaks, where peak assignment is necessarily approximate. Nonetheless, the spectral changes which correspond to aging can readily be identified.

In the case of anatase pigmented samples, UV irradiation produced spectra comparable to those reported for degradation of unpigmented linseed oil (aged thermally, under natural conditions, or by UV acceleration^{4,7,11,35}). The intensity of the broad carbonyl peak (C=O stretch, centred on 1736 cm^{-1}) and hydroxyl region (OH stretch, $2500\text{-}3300\text{ cm}^{-1}$) increased relative to that of characteristic CH absorbance peaks; at 2930 cm^{-1} and 2880 cm^{-1} (CH stretches), 1464 cm^{-1} (CH_2 scissoring) and 1378 cm^{-1} (CH_2 wag)¹¹, Figure 1. This has been attributed to the release of volatile short chain alkanes during degradation, in keeping with the literature.^{7,21,36} Furthermore, both the carbonyl and hydroxyl peaks broaden significantly, indicating that an increased range of oxygen functional groups are formed.

In order to assess the effect of UV irradiation in more detail, carbonyl regions were averaged, baseline corrected and normalised relative to the ester peak (at 1736 cm^{-1}), Figure 2. It can be seen that upon initial UV exposure, similar features are observed for both the samples containing uncoated anatase pigments (highly photocatalytic) and coated rutile pigments (considered inactive). For example, the broad absorbance around 1640 cm^{-1} , related to the presence of carboxylic acids and

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3 aldehydes, and at 1717 cm^{-1} , attributed to free acids and ketones, increase in
4 intensity relative to the ester peak. Acid and aldehyde end groups are formed
5 following cleavage around ester groups, β -scission and oxidation reactions, Scheme
6 4a.^{7,35} Whilst the broad absorbance centred at 1640 cm^{-1} is potentially also
7 associated with conjugated C=C functionalities (Table 2), we ascribe this absorbance
8 to low molecular weight carboxylic acids and aldehydes, since these are known
9 products of linseed oil oxidation.^{8,9,36,37,38} Following the initial UV exposure, the
10 chemical state of the rutile containing samples appears to stabilise, whereas this
11 absorbance peak continues to grow for anatase-containing samples, confirming that
12 the presence of photocatalytic anatase leads to increased oxidative degradation. In
13 addition, it is notable that the intensity of absorbance at higher wavenumbers (around
14 1780 cm^{-1}) increased upon UV irradiation. This has previously been proposed as a
15 diagnostic peak for linseed oil aging.¹¹ Whilst this peak is consistent with the
16 presence of peracids, peresters, lactones or anhydrides, absorbance in this region is
17 widely attributed to lactone formation during the oxidative degradation of ester-
18 containing polymers (e.g., during thermal and UV accelerated aging of acrylic
19 resins,^{39,40,41,42,43,44} via various proposed mechanisms, e.g., Scheme 4b). However, in
20 contrast to the progressively increasing absorbance noted at lower wavenumbers,
21 the intensity of this peak stabilised after the initial UV dose for both rutile and anatase
22 samples.
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52 Scheme 4. Suggested mechanistic pathways for the degradation of linseed oil paint: (a) the
53 formation of aldehydes and carboxylic acids by β -scission and oxidation; and (b) the
54 formation of γ -lactones.
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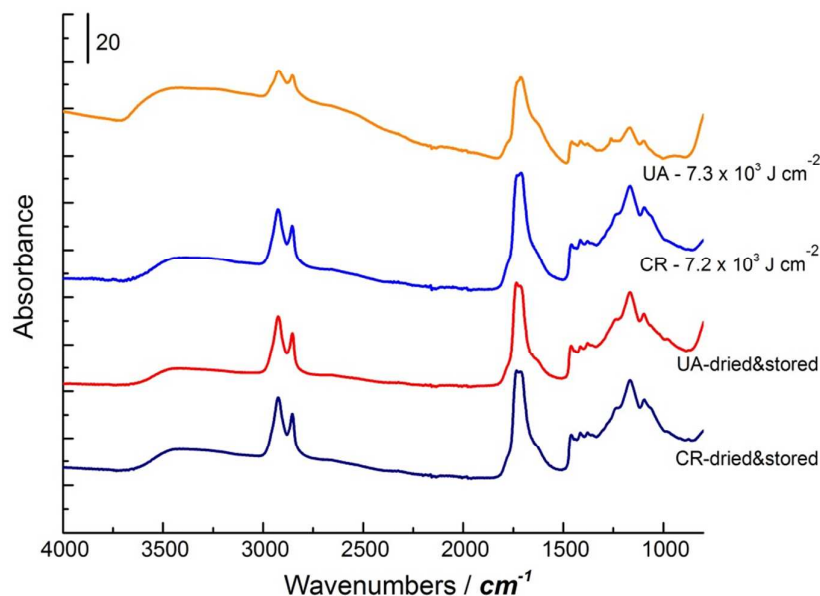


Figure 1: ATR mode FTIR spectra of linseed oil samples pigmented with uncoated anatase (UA) or coated rutile (CR) after drying under ambient conditions for 14 days and storage, and after drying under ambient conditions for 14 days followed by exposure to $7.3 \times 10^3 \text{ J cm}^{-2}$ UV or $7.2 \times 10^3 \text{ J cm}^{-2}$ UV respectively.

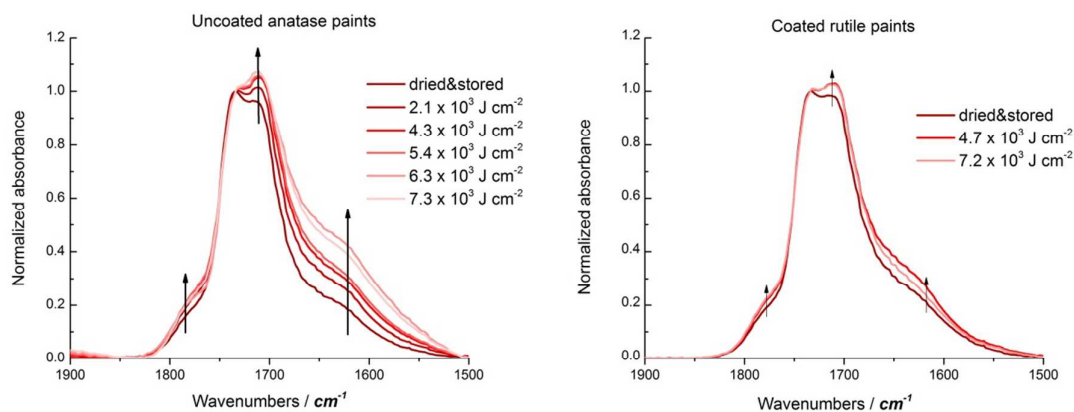


Figure 2. Baseline corrected infrared spectra for linseed oil samples pigmented with 15 % PVC anatase or rutile forms of TiO_2 before and after increasing levels of exposure to UV. Spectra are normalised to the 1736 cm^{-1} ester peak, and each spectrum is the mean of 5 individual spectra gathered from various positions.

Table 2: Linseed oil infrared peak assignments.

Wavenumber	Peak assignment
~3393 cm ⁻¹	hydroperoxide, alcohol and acid O-H stretch
2919 cm ⁻¹	alkyl CH-CH ₂ C-H stretch
2852 cm ⁻¹	alkyl CH-CH ₂ and CH ₃ C-H stretch
~2650 cm ⁻¹	O-H from (-OH)COOH, broadening of O-H due to carboxylic acids.
1780 cm ⁻¹	peracids, peresters, γ -lactones and anhydrides C=O stretch.
1736 cm ⁻¹	ester C=O stretch.
1717 cm ⁻¹	saturated ketones and free fatty acid C=O stretch.
~1640 cm ⁻¹	Conjugated C=C stretch, acid or aldehyde C=O stretch
~1613 cm ⁻¹	Aldehyde, carboxylic acids and α/β unsaturated ketone C=O stretch.
1463 cm ⁻¹	Alkyl CH-CH ₂ , CH ₃ C-H bending
1410 cm ⁻¹	Acid C-O bend, -CH ₂ -CO-O C-H bending
1377 cm ⁻¹	Alkyl CH ₂ C-H bending
1054 cm ⁻¹	Alcohol C-O stretch.

AFM-IR

Localised infrared spectra were initially obtained for the anatase paints before and after extensive UV irradiation (step 5). This was achieved by positioning the AFM-IR probe in contact with the sample surface, and stepping pulsed radiation incident on the probe tip through the mid-IR fingerprint range (900 cm⁻¹ – 1900 cm⁻¹). The amplitude of probe oscillations induced by thermal expansion of the sample (IR amplitude) was then monitored and plotted to produce spectra, where peak positions were found to be in broad agreement with those produced using bulk ATR FTIR, Figure 3.

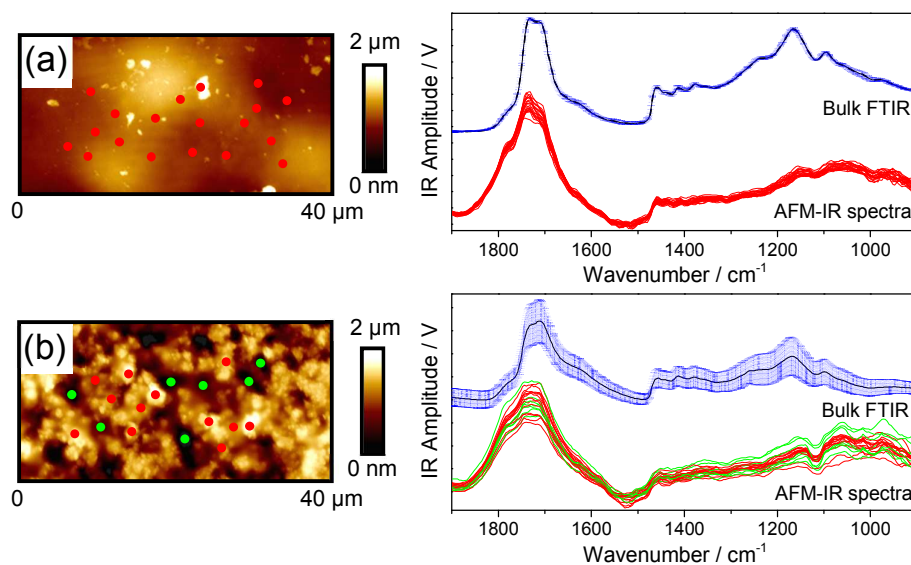
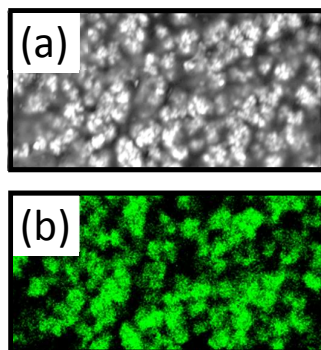


Figure 3. AFM-IR contact mode height images (left) alongside ATR-FTIR spectra and AFM-IR spectra (right) corresponding to tip locations indicated by markers for samples of linseed oil pigmented with uncoated anatase after (a) drying under ambient conditions for 14 days and dark storage; (b) drying under ambient conditions for 14 days followed by exposure to $7.3 \times 10^3 \text{ J cm}^{-2}$ UV (irradiation step 5). ATR-IR spectra correspond to the mean of 5 individual measurements, and error bars correspond to 1 standard deviation.

Contact mode AFM height profiles revealed increasing surface roughness of the paints pigmented with anatase during UV irradiation, in keeping with previously reported tapping mode AFM images and gloss measurements,¹⁶ Figure 3. XPS analysis has previously shown that titanium is detected in concert with this roughening, indicating that pigments become gradually exposed.¹⁶ To verify this, SEM analysis and EDX mapping was performed, which demonstrated that raised areas indeed correspond to locally increased concentrations of titanium at the surface, Figure 4.

For the rougher, aged specimens, local AFM-IR spectral intensity was found to vary more across the sample, Figure 3. A similar effect was observed for bulk infrared spectra, where variations were found to increase dramatically after UV doses of $5.4 \times 10^3 \text{ J cm}^{-2}$ or more. The intensity of local AFM-IR spectra did not however specifically correlate to 'high' or 'low' areas of the surface profile, Figure 3b. The relative signal intensity is instead proposed to change as a result of both chemical heterogeneity and local variations in the effective sampling volume caused by the presence of underlying pigment particles. This is because during AFM-IR, the sampling volume is not limited by the penetration of infrared radiation, but by the volume of material under the AFM-IR probe tip that contributes to the thermal

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3 expansion 'felt' by the probe. Both the thermal expansion co-efficient and infrared
4 absorbance of titanium dioxide are negligible in comparison to the organic binder, so
5 the effective sampling depth is considered to be limited to material between the
6 probe and nearest underlying pigment.
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23 Figure 4. 20 μm x 10 μm scanning electron microscopy images of the model anatase
24 pigmented linseed oil paint surface following drying under ambient conditions for 14 days and
25 exposure to $7.3 \times 10^3 \text{ J cm}^{-2}$ UV (irradiation step 5): (a) secondary electron image and (b)
26 energy dispersive x-ray spectroscopy map for titanium.
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29 In light of this, direct comparison of the UV irradiated anatase samples was
30 achieved using averaged AFM-IR spectra normalized to the ester C=O absorbance
31 at 1736 cm^{-1} , similar to the bulk FTIR analysis presented in Figure 2. Inspection of
32 the carbonyl region after UV exposure revealed a relative increase in absorbance
33 associated with degradation products, namely carboxylic acids and aldehydes at
34 1640 cm^{-1} , free acids and ketones at 1710 cm^{-1} and lactones at 1780 cm^{-1} , Figure 5.⁴⁵
35 Note that whilst these spectral changes appear minor, this analysis was repeated in
36 three different regions for each sample, and the relative changes in absorbance were
37 found to be consistent within each data set. It was, however, noted that the
38 absorption at 1780 cm^{-1} appears far more pronounced in the AFM-IR spectra than in
39 ATR-FTIR, whereas the increases in absorbance at lower wavenumbers (1710 and
40 1640 cm^{-1}) are less prominent. This can be potentially be explained by the difference
41 in detection techniques (i.e., a difference in the thermal expansion coefficients for
42 various chemical species) or a concentration gradient at the paint surface, since
43 AFM-IR is expected to be more surface sensitive. In reality, both effects appear to
44 contribute; the presence of a concentration gradient through samples was verified by
45 AFM-IR analysis on the reverse of paint specimens, removed from the Melinex
46 support using a scalpel, Figure 6.
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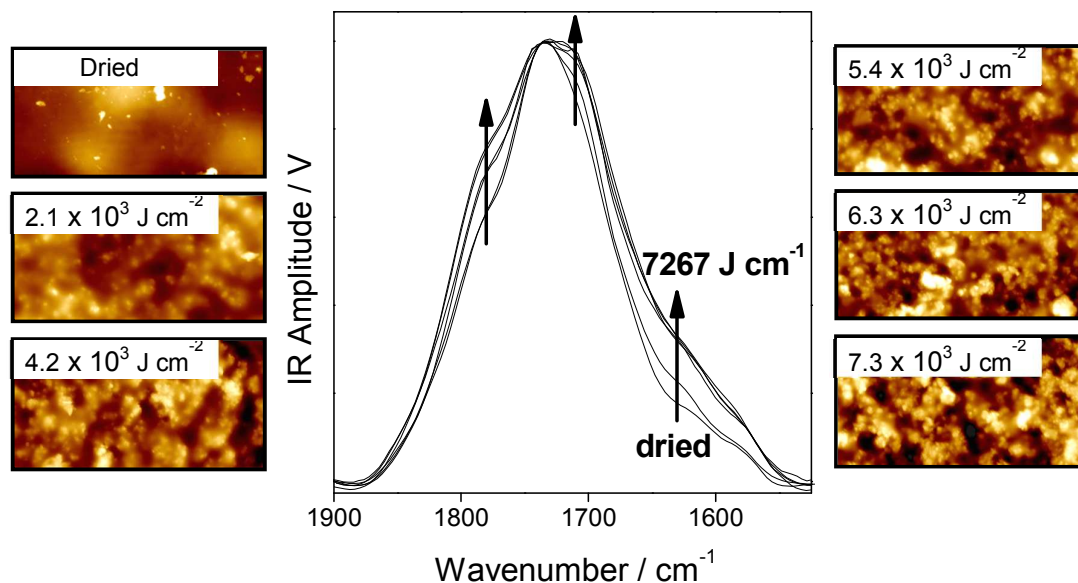


Figure 5. 40 μm x 20 μm contact mode AFM images of linseed oil samples pigmented with uncoated anatase after drying under ambient conditions for 14 days, and after exposure to increasing UV doses (irradiation steps 1 to 5), alongside the carbonyl region of AFM-IR spectra produced by averaging 20 AFM-IR spectra gathered from random positions within each of these regions. For comparison, spectra are normalised to the 1736 cm^{-1} ester band. Z scale for AFM images is 2 μm .

Due to the imprecise detachment method, direct comparison between the spectra gathered from reverse side of different samples is not possible (the apparent roughness of the reverse of aged rutile pigmented samples is a sampling artefact). Nonetheless, carbonyl peaks detected at the back of detached paint films were consistently found to be more defined than those gathered from the front, i.e., the shoulder peaks associated with degradation were comparatively attenuated, Figure 6. Interestingly, this was also found to be the case for anatase pigmented samples examined before UV aging, and control samples prepared using the less active coated rutile form of titanium white. This can be explained by consideration of the linseed oil curing and aging mechanisms, since whilst the precise penetration depth of UV, moisture and oxygen are not known, the outer surface of the paints is more exposed. Indeed, Zumbühl et al. recently demonstrated gradients of oxidation in oil paint cross sections using ATR-FTIR spectroscopy,³⁷ finding high concentrations of polar chemical groups toward paint surfaces, and this is in line with the reported preferential formation of azeleic acids at the surface⁹. In the present case, natural aging and photocatalytic aging can be seen to induce similar spectral changes but at a significantly different rate, which is in keeping with the titanium white acting as a radical initiator (a direct comparison between spectra gathered from the surface of

UV aged anatase and rutile spectra is given in Figure 7). In the case of rutile control samples however, the UV-induced process is sufficiently retarded that spectra obtained from the front of samples change little as a consequence of UV irradiation, and no increases in roughness are observed.

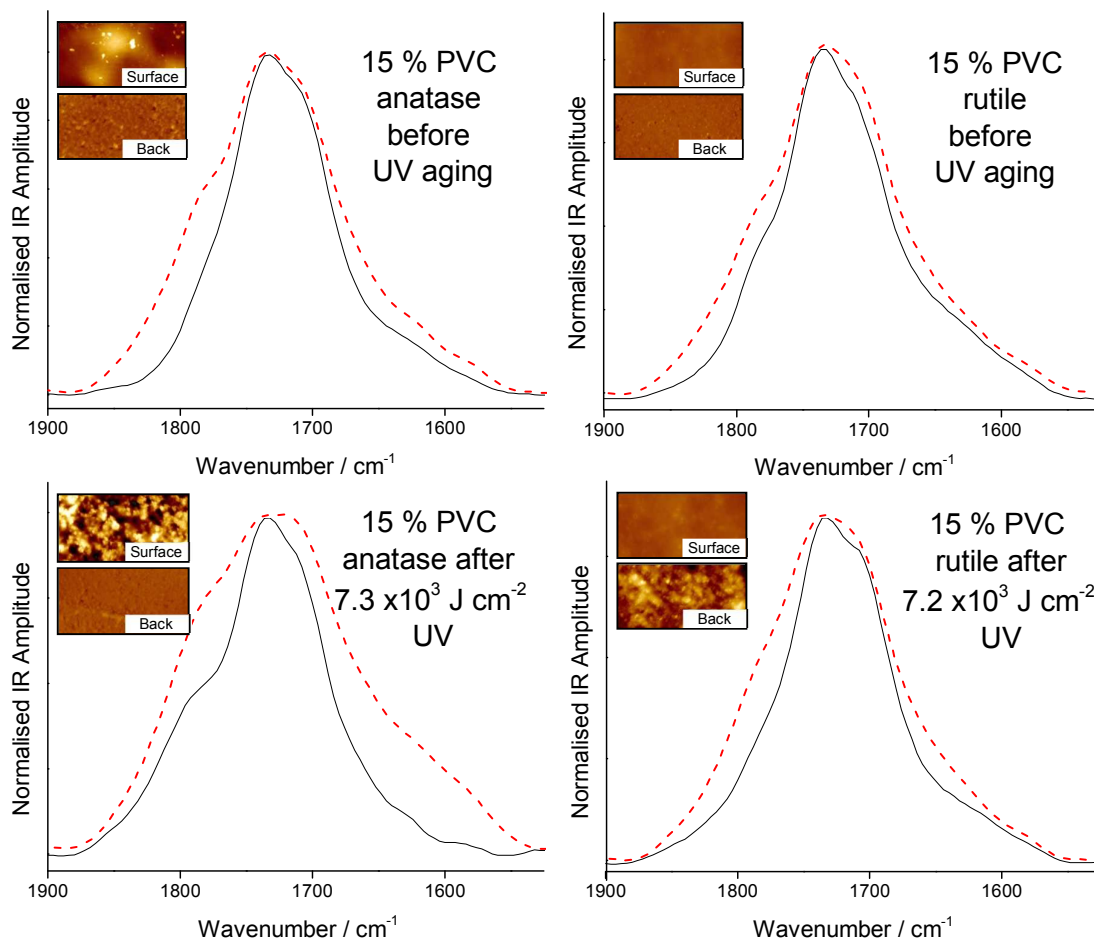


Figure 6. AFM-IR contact mode height images (z scale is 2 μm) and the carbonyl region of spectra produced by averaging 20 AFM-IR spectra taken from random positions within the imaged region. Spectra were gathered from the front (red dashed line) and reverse (black solid line) side of linseed oil samples pigmented with the uncoated anatase and coated rutile forms of titanium dioxide before and after extensive UV aging (irradiation step 5).

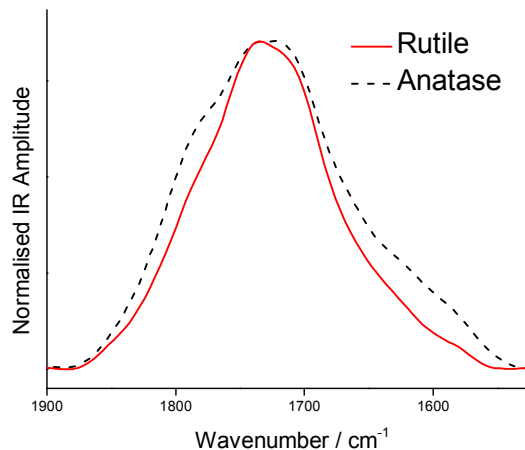


Figure 7. Comparison of the carbonyl region of spectra produced by averaging 20 AFM-IR spectra taken from the surface of linseed oil samples pigmented with the uncoated anatase (black dashed line) and coated rutile (red line) forms of titanium dioxide after drying under ambient conditions for 14 days and exposure to $7.3 \times 10^3 \text{ J cm}^{-2}$ and 7.2×10^3 doses of UV respectively (irradiation step 5).

The generation of degradation products at the surface of the anatase-pigmented paints was further investigated by AFM-IR mapping, Figure 8. Infrared amplitude maps were gathered at 1640 cm^{-1} (corresponding to carboxylic acid and aldehyde groups produced during aging), 1736 cm^{-1} (corresponding to ester groups) and 1780 cm^{-1} (corresponding to lactone groups produced during aging), and these varied in line with height images. This confirms that the local amplitude signal corresponds to the effective sampling volume between the probe tip and underlying pigment particles.⁴⁶ In order to overcome this and isolate chemical differences, ratio images were generated by division of the infrared amplitude data gathered at different wavenumbers, Figure 8. In the case of dried and stored samples which had not been exposed to UV aging, ratio images generated from $1640 \text{ cm}^{-1} / 1736 \text{ cm}^{-1}$ (showing the location of carboxylic acid and aldehyde degradation products in relation to esters) and $1780 \text{ cm}^{-1} / 1736 \text{ cm}^{-1}$ (corresponding to the location of lactones in relation to esters) were relatively homogeneous, confirming that differences in the amplitude signal due to sampling volume effectively cancel out. In contrast, immediately after exposure to UV ($2.1 \times 10^3 \text{ J cm}^{-2}$ dose), ratio images revealed a heterogeneous distribution of degradation products around raised areas (e.g., circled regions, central column of Figure 8) which are attributed to anatase pigment clusters. Further UV exposure yielded more homogeneous ratio images, (obtained under identical imaging conditions), indicating increased coverage of the surface with degradation products.

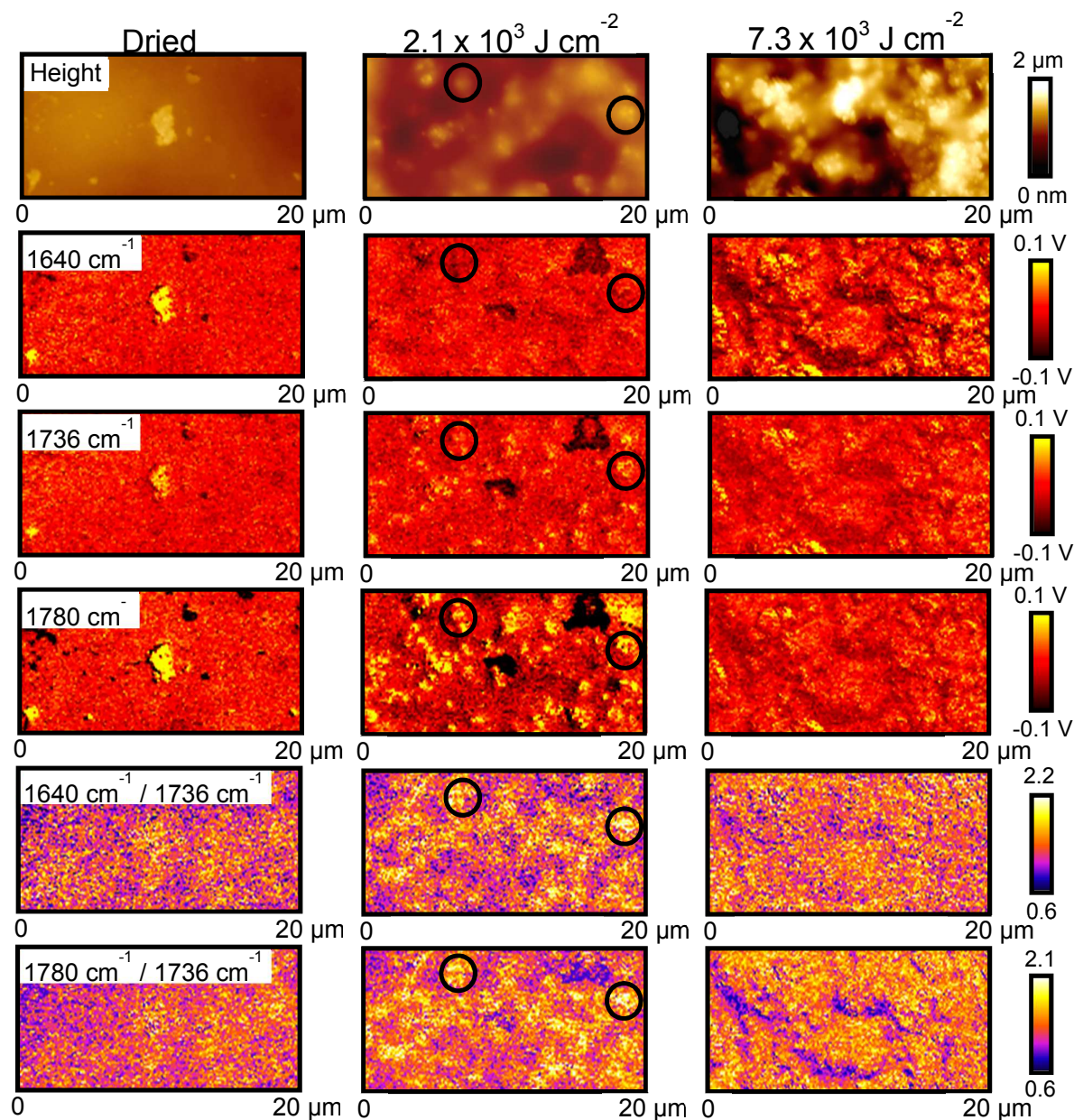


Figure 8. 20 μm x 10 μm AFM-IR height images and corresponding infrared maps of linseed oil paint pigmented with anatase after drying under ambient conditions for 14 days, after exposure to $2.1 \times 10^3 \text{ J cm}^{-2}$ UV (irradiation step 1), and after exposure $7.3 \times 10^3 \text{ J cm}^{-2}$ UV (irradiation step 5). To identify local variations in signal, IR amplitude images gathered at 1640 cm^{-1} , 1736 cm^{-1} and 1780 cm^{-1} are flattened by centring each scan line around zero. Ratio images generated from raw data are also presented for $1640 \text{ cm}^{-1} / 1736 \text{ cm}^{-1}$ (showing the location of carboxylic acid functional groups) and $1780 \text{ cm}^{-1} / 1736 \text{ cm}^{-1}$ (corresponding to the location of lactone functional groups).

Discussion

Numerous investigators have previously reported FTIR analysis of linseed oil paint degradation, describing the appearance of characteristic absorbance peaks which may be of use in a diagnostic device^{7,11,21}. In the present case, infrared spectra revealed that the breakdown of linseed oil containing anatase pigments generally involves increased absorbance at wavenumbers consistent with lactone, carboxylic acid and aldehyde species, alongside the release of short chain volatiles. However, the concentration of lactones stabilised rapidly, and its role in degradation is unclear. In the case of carboxylic acids, it has been documented that hydrolytic attack may lead to the preferential formation of short chain di-carboxylic acids near the surface of oil paint samples.^{8,9,37,38} The origin of detected carboxylic acid species within a given sample (i.e., hydrolysis or photocatalytic radical attack), cannot be gauged directly using infrared techniques, precluding the use of this absorbance as a direct measure of catalytic activity. Nonetheless, comparison of AFM-IR and ATR-IR analysis of rutile and anatase pigmented paint performed here gives some insights into the degradation mechanism, pointing towards a predominately photocatalytic radical-induced mechanism for the formation of carboxylic acids and aldehydes in the presence of anatase pigments.

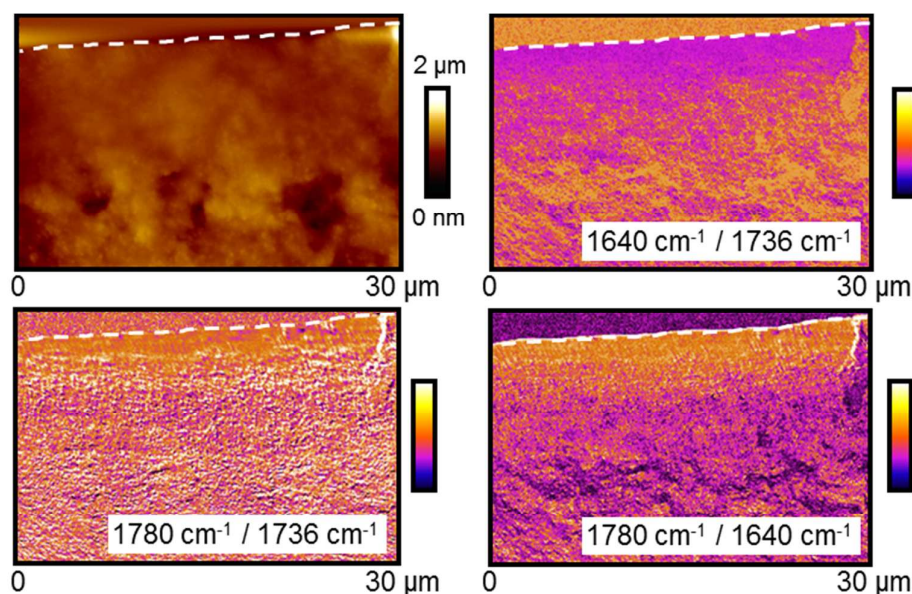
Oxidation and hydrolysis during drying is supported by the fact that the surface of both anatase and rutile pigmented samples were found to differ substantially from the bulk prior to UV aging. The formation of carboxylic acids and aldehydes concentrated towards the surface is expected, since the outer surface of the paint sample is directly exposed to ambient oxygen, humidity and light. Whilst ATR-FTIR spectra indicate that this process continues on initial illumination with UV, in the case of rutile pigmented samples the chemical state then stabilised. This may be because the relatively inactive rutile pigments provide a protective effect by absorbing UV without producing further radicals, preventing degradation deeper in the film (i.e., UV-initiated oxidation is limited to the exposed surface, and the reactions producing lactone, aldehyde and acid species are therefore slowed in comparison to the anatase samples). In contrast, chemical change continued for anatase paints, and this is characteristic of a photocatalytic process, where UV illumination of the semi-conductor pigment provides reactive electrons at the surface of particles to initiate further degradation.

In the case of lactones, ATR-FTIR analysis indicated that their formation occurs immediately upon UV illumination, but then rapidly stabilised, even as degradation visibly continued. This indicates that lactones are a transient species

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3 formed during linseed oil degradation. Indeed, AFM-IR analysis confirmed that
4 lactones are concentrated towards the sample surface, where the greatest degree of
5 oxidation is expected to occur. In contrast, the measured absorbance of other
6 degradation products (acids, aldehydes and ketones) was found to stabilise when
7 measured using AFM-IR, whilst continuing to increase in the less surface sensitive
8 bulk FTIR spectra. Given that AFM-IR mapping also showed a relatively
9 homogeneous concentration of degradation products is ultimately established across
10 the paint surface, we propose that within the sampling depth of AFM-IR, a dynamic
11 surface layer is formed where the generation of degradation products is matched by
12 their further breakdown and release as volatile species. It is suggested that lactones
13 are predominately produced within this region, leading to increasing absorbance in
14 the AFM-IR spectra until full surface coverage is achieved. Upon further UV
15 exposure, acids, aldehydes and ketones are generated deeper inside the paint and
16 their increasing absorbance can be detected using ATR-FTIR (but not AFM-IR).
17 Support for this proposed mechanism was found by cross-sectional AFM-IR analysis
18 of an anatase pigmented sample cut after UV aging (irradiation step 5). Lactone
19 absorbance was found to be concentrated towards the paint film surface, whereas
20 absorbance associated with acids and aldehydes was found to be more intense deeper
21 inside the coating, Figure 9. Note, however, that this cross-section was prepared
22 using a scalpel under ambient conditions and this places limitations on any further
23 interpretation of the data (due to an imprecise cutting angle, potential smearing of
24 degradation products etc.).

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26 A previously suggested disadvantage of infrared spectroscopy in
27 conservation science is that significant changes in the detected peak positions and
28 intensities coincide with visible paint degradation.¹⁶ In the present case, visible
29 degradation was only evident in the case of anatase samples exposed to UV doses
30 of $6.3 \times 10^3 \text{ J cm}^{-2}$ or more, whereas normalised FTIR spectra showed significant
31 changes for the degrading paint well in advance of this exposure, Figure 3. From the
32 discussion above it is however evident that infrared absorbance at a given
33 wavelength cannot be used to directly ascertain the level of degradation. Instead, a
34 better approach would be to monitor the carboxylic acid/aldehyde absorbance
35 relative to that of esters. Despite the overlapping, broad nature of these peaks, the
36 relative changes described were consistently detected for degraded paint specimens
37 using both infrared spectroscopy techniques. Nonetheless, this alone cannot provide
38 a direct measure of the level of degradation, since both species are formed during
39 drying and aging, and furthermore, initial concentrations will depend on the source of
40 linseed oil. Monitoring the changes in this ratio over time will, however, give an
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3 indication of the degradation kinetics. This opens up the tantalising possibility that the
4 emerging field of handheld infrared technologies could provide a convenient non-
5 destructive diagnostic device in the field of cultural heritage.⁴⁷ This would require a
6 systematic and long term approach for preventive condition monitoring within art
7 collections, taking spectra at fixed locations on a painting at specific time intervals (3,
8 5, 10 years) and is of potential interest not only for photocatalytic degradation in the
9 presence of titanium white, but also to monitor natural aging and other degradation
10 phenomena such as soap formation below the surface.
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38 Figure 9. 30 μm x 20 μm AFM-IR height and ratio images corresponding to an uncoated
39 anatase pigmented linseed oil paint cross-section exposed to a $7.3 \times 10^3 \text{ J cm}^{-2}$ dose of UV
40 (irradiation step 5), held at 90° immediately after cutting through with a scalpel (no
41 embedding). White dashed lines correspond to the outer surface of the paint, ratio images
42 correlate to the location of carboxylic acids and aldehydes relative to esters ($1640 \text{ cm}^{-1} / 1736$
43 cm^{-1}); lactones relative to esters ($1780 \text{ cm}^{-1} / 1736 \text{ cm}^{-1}$) and lactones relative to carboxylic
44 acids and aldehydes ($1780 \text{ cm}^{-1} / 1640 \text{ cm}^{-1}$).
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46 Finally, it is noteworthy that the results presented in this paper represent the
47 first application of sub-diffraction limit infrared mapping to pigmented coatings,
48 demonstrating the potential of the recently developed AFM-IR technique in this field.
49 This approach could be used to generate further insights in cultural heritage
50 research, where envisioned examples include the spatially resolved characterization
51 of local drying and aging effects, the study of metal soap formation, detailed pigment-
52 binder interactions^{12,23}, and cleaning studies on reconstructed paint samples (e.g.,
53 mapping the residues of the cleaning agent on the paint surface).^{10,48}
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Conclusions

Sub-diffraction limit AFM-IR imaging has provided direct evidence for locally induced photocatalytic degradation in the vicinity of anatase titanium white pigments at the surface of linseed oil paints. A spectral signature associated with the products of radical oxygenation reactions has been identified, and this can also be detected using bulk FTIR methods prior to visible degradation. Moreover, the combination of these varying surface sensitive techniques has been used to differentiate between the relative concentrations of degradation products through the depth of paint films.

Acknowledgments

The authors are grateful to AkzoNobel for financial support, materials, and S. Gibbon and B. Rossenaar specifically for their expertise. Suzan de Groot is acknowledged for training on the ATR-FTIR. The authors also thank J. Hermans and K. Keune for fruitful discussions and help with interpretation. Finally P.Kooyman is acknowledged for her involvement in Van Driel's PhD research.

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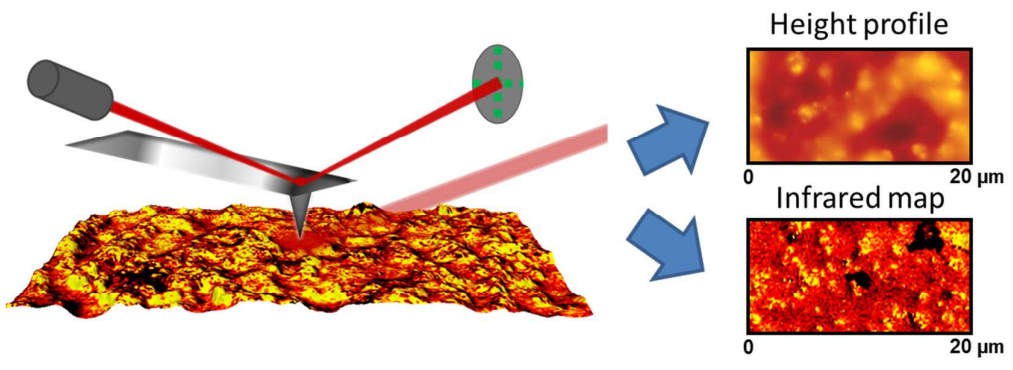
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