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PAINTINGS

Canvas-related microcracks in Danish 19th-century paintings

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Abstract
This paper discusses the emergence of microcracks observed in the ground layers of paintings on canvas supports. Such cracks are visible in 50 µm resolution x-radiographs and correlate with the occurrence of microcracks as well as more large-scale crack patterns in the surface of the paintings. They also explain the initiation of one type of crack formation and the subsequent propagation of the crack into the paint layers. An examination of 41 paintings by the Danish artist C.W. Eckersberg, dating from throughout his oeuvre, showed a variable prevalence of microcracks in 24 paintings. Some cracks were visible only in the x-radiographs while others could be observed also on the paint surface. In many cases, it was found that microcracks were incorporated into the larger crack pattern of the paint. The mechanical process underlying the genesis of microcracks is discussed, and a potential association with the stratigraphy of the grounds used in Eckersberg's paintings is proposed.

INTRODUCTION

In preparation for the exhibition *A Beautiful Lie – Eckersberg* (8 October 2015–24 January 2016) at Statens Museum for Kunst (the National Gallery of Denmark), a large number of paintings by the Danish artist C.W. Eckersberg (1783–1853) were examined. The results shed light on the technique of the painter, who was a professor at The Royal Danish Academy – Architecture, Design, Conservation and a major inspiration for a generation of painters in Denmark in the first half of the 19th century. During examination by x-radiography, a phenomenon was observed that warranted further investigation. Processing of the 50 µm resolution x-radiographs revealed not only the weave geometry of the canvases (Filtenborg and Andersen 2016), following the method of Johnson et al. (2011), but also a large number of minor cracks in the ground layer of some of the paintings. In many cases, these cracks were not visible on the surface of the paintings. The cracks in the ground were parallel to the fibres (spinning angle) in the threads of the canvas and positioned where the ground layer was thinnest, i.e. on top of two threads crossing in the weave. As a similar feature had been observed previously in other paintings and in commercially prepared canvases, the Eckersberg paintings presented an opportunity to examine a larger group of paintings – well-defined in terms of their structure and materials, as they have already been investigated in a number of studies – for this type of cracks. The hypothesis was that the location and morphology of the microcracks were the product of the structural interaction between ground and canvas and would provide insights into one type of crack initiation in oil paintings.

Cracks in canvas paintings have been the focus of a number of publications, and different ways of categorising them have been proposed. Keck (1969) defined drying cracks and ageing cracks, a distinction still used by conservators, even though the causes of the two types of cracks and how they can be distinguished and sub-categorised are not entirely evident. Drying (cross linking through oxygen uptake) and ageing (oxidation and hydrolysis) in oil paints have also been studied and it is clear that the two processes can take place simultaneously (see, for example, Burnstock and van den Berg 2014). Bucklow (1999) related different crack patterns to different paint materials and painting techniques. The forces resulting in crack formation have been investigated as well. Studies of material deformation and failure criteria have laid the foundations for climate regulation standards in collections and for the transportation of artworks.

Safe climate fluctuation ranges have been derived from criteria based on yield strength or failure and the related structural properties of the materials (Mecklenburg 2007a and 2007b). The aim was to prevent environmental fluctuations of a magnitude sufficient to cause permanent deformation and/or cracks in the materials. Characterisations of painting materials have therefore been important in order to relate basic mechanical properties to crack formation, an issue discussed in a number of publications (Elm 1953, Mecklenburg et al. 2005, Andersen et al. 2019). Computer analyses of complete paintings (Mecklenburg et al. 1994, De Willigen 1999) or paint sections (Wood et al. 2018) have been performed, with a discussion of the effect of fatigue on paint fracture included in the latter publication.

The chronology of crack development must be understood in order to explain crack patterns. According to Paquette et al. (2002), paint cracking occurs in distinct phases: (1) tensile stress; (2) crack; (3) deformation (crack opening); (4) decrease in tensile stress; (5) increase in shear stress (paint substrate); (6) loss of adhesion (to substrate); and (7) peeling. In other words, tensile stress initiates the crack while the subsequent steps ultimately lead to detachment of the paint if enough stress is present. The amount of stress required to cause a crack depends on the thickness and strength of the ground and paint layers. Since stress is defined as force per cross-sectional area, a thinner layer should be more likely to break than a thick layer, if the two layers have the same mechanical properties. If a microcrack develops, it is likely to grow since it usually takes more energy to create a crack than to propagate it (Smith et al. 2001). Paquette et al. (2002) found that the creation and propagation of cracks can be due, for example, to wood fibres in the base layer that induce directional variations in stress and strength. In the present study, we propose that the same dependency can be assumed for cracks in layers on canvas supports.

Crack growth can continue until crack saturation is reached, as described for painted wood (Bratasz and Vaziri Sereshk 2018). Recognition of these steps of progression in crack formation enables an assessment of the stage of deterioration in a painting. This was the case with the microcracks observed in Eckerberg's paintings, which, according to our analysis, contributed to the initiation of larger crack patterns.

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The 41 paintings by C.W. Eckersberg examined for this study were those which, in a previous investigation (Filtenborg and Andersen 2016), were studied for their grounds and canvas supports, with the findings then related to information from contemporary written sources such as Eckersberg's diary notes. The grounds were generally white or pale in colour and in some cases a red, brown or yellow layer was detected underneath. The canvases were linen with a plain weave in all instances but one, and with a thread count ranging from 7.4 to 18.3 threads per cm. The paintings from Eckersberg's sojourn to Paris and Rome (1810–16) were generally on canvases with thread counts at the lower end of the range. Investigations into the pigment and binding media used in the grounds of Danish Golden Age paintings showed that the binding medium was egg and oil in nine examined paintings (including three by Eckersberg) and the dominant

Figure 1. *A Pergola,* C.W. Eckersberg, Italy. 1814/16. Oil on canvas, 34 × 28.5 cm, Statens Museum for Kunst, KMS2059. The area shown in detail in Figure 2 is marked with white lines (SMK Photography/Jakob Skou-Hansen)

Figure 2. *A Pergola,* Eckersberg, Italy. 1814/16, 400 × 400 pixel (20 × 20 mm) detail of Figure 1, covering the area of Figures 3, 4 and 7 (SMK Photography; KADK Mikkel Scharff image enhancement)

pigments were lead white and calcium carbonate/chalk (Andersen et al. 2017). Glue sizing was not confirmed in those paintings. Conservation treatments of the examined paintings in this study were not taken into account due to a lack of data concerning the extent of the microcracks before these interventions.

METHOD

X-radiographs were made using an Yxlon Y Smart 160E x-ray tube and control unit on Dürr NDT CRIP3040109 digital image plates, type HD, 300 × 400 mm, and scanned in a Dürr HD-CR 35 NDT laser scanner with a resolution of 50 µm per pixel. One painting, *A Pergola* (Figure 1), was also scanned at a resolution of 25 µm per pixel. The exposure parameters were 5 mA, 25–28 kV and 90 seconds, with a film-focus distance of 55 cm. The scanned x-radiographs were saved as 16-bit TIFF files for later examination and processing.

A subset of x-radiographs, from 24 paintings, were examined and processed using the image processing software VIPS/nip2 version 8.7.0 (Martinez and Cupitt 2005). For all x-radiographs examined, a processing protocol was established and applied. A representative area of 400 × 400 pixels was selected on each 16-bit x-radiograph one-band TIFF file. The area was filtered using a Fourier/Butterworth/ring pass filter (if necessary, with minor ajustments of the frequency or amplitude cutoff standard values in the program). This created consistent image areas where the usual contrast between the weave pattern and the difference in absorption of the ground and paint structure were supressed/equalised, thus enhancing the visibility of the crack pattern and rendering the sample areas comparable across all of the examined paintings. As the pixel size (50 µm) was pre-defined, the average size of the minute cracks (width and length) could be measured on the image files with reasonable precision.

RESULTS

Observations of the crack patterns in the paintings by C.W. Eckersberg using 50 µm resolution x-radiographs revealed canvas-related microcracking in the paintings and its relation to crack occurrence in the paint layer. Microcracks were found in 24 of the 41 paintings, and in some cases those in the ground evidently had led to cracks in the paint layers. Table 1 shows the examined paintings, with colour coding of the individual extent of the microcracks roughly quantified by examination of the x-ray images. As indicated by the red colour in the table, two early-career paintings (*Loki and Sigyn* and *Landscape with a Stile. The Isle of Møn*) and the paintings executed in Rome (1814–16) (*Portrait of Bertel Thorvaldsen, View of the Garden of the Villa Borghese in Rome*, *Portrait of the Model Maddalena or Anna Maria Uhden* and *A View across the Tiber from Trastevere towards Castel S. Angelo*), were more prone than the other paintings to microcracks (Figures 2–4). This was also the case with the two paintings from the end of Eckersberg's career, dated 1845 and 1847. During his sojourn in Rome, the artist used relatively coarse canvases with a low thread count. Furthermore, the majority of these canvases, as well as one of the last two paintings from 1845 and 1847 have a double ground, with presumably relatively hygroscopic earth pigments or an earth pigment mixed into a single ground in the lower layer. Earth pigment grounds are generally presumed to be more hygroscopic and have less mechanical strength than a ground predominantly containing lead white (Mecklenburg 2007a).

Table 1. Overview of the Eckersberg paintings in the study. For the paintings highlighted in red the x-radiographs clearly showed microcracking. For those highlighted in green, the microcracks were faintly or only locally visible. Paintings without highlighting had few or no visible microcracks

Accession no.	Title and dimensions (cm)	Year	Thread count	Ground (lower ground, upper ground)
KMS7379	*Alexander the Great on his Sickbed, 54.5 × 65.5*	1806	12.1 × 10.7	Single white
KMS1764	*Self-Portrait, 33.0 × 26.0*	1807/10	9.1 × 11.5	Painted on top of another composition. Three-layer ground (yellow, red, white)
KMS39	*Loki and Sigyn, 134.0 × 162.5*	1810	13.0 × 13.8	Single (pale red)
KMS7694	*Landscape with a Stile. The Isle of Møn, 58.0 × 74.8*	1810	9.1 × 9.2	Single (pale red)
KMS1624	*Pont Royal seen from Quai Voltaire, 55.5 × 71.0*	1812	8.9 × 9.6	Double (red and white)
KMS7256	*The Return of Ulysses. Scene from Homer's Ulysses, 60.0 × 72.0*	1812	13.5 × 12.7	Single (white)
KMS1333	*Two Shepherds, 55.5 × 71.0*	1813	7.8 × 9.5	Double (red, white/pale grey)
KMS1623	*A View from the Château of Meudon, 55.5 × 71.0*	1813	9.3 × 9.3	Double (red, white)
KMS1769	*Alcyone's Farewell to her Husband. From Ovid's Metamorphoses, Song XI, 72.5 × 48.5*	1813	15.6 × 13.9	Double (yellowish white, white)
KS38	*Portrait of Bertel Thorvaldsen, 90.7 × 74.3*	1814	7.9 × 7.3	Double (yellowish white, white)
KMS1310	*View of the Garden of the Villa Borghese in Rome, 28.0 × 32.5*	1814	10.0 × 9.0	Single white
DHS107	*Portrait of the Model Maddalena or Anna Maria Uhden, 31.0 × 21.3*	ca. 1815	9.9 × 10.0	Not known
KMS1346	*A View across the Tiber from Trastevere towards Castel S. Angelo, 28.5 × 44.0*	ca. 1815	11.7 × 9.5	Double (yellowish white, white)
KMS2093	*View of the Tiber near Ponte Rotto in Rome, 28.0 × 44.0*	ca. 1815	11.7 × 9.5	Double (yellowish, white)
KMS2058	*View of the Gardens of the Villa Albani. Rome, 27.0 × 34.5*	1814-16	9.2 × 9.3	Not known
KMS2059	*A Pergola, Italy, 34.0 × 28.5*	1814-16	9.8 × 9.1	Yellow single
KMS2099	*View from the Fontana Acetosa, Rome, 25.5 × 44.5*	1814-16	7.7 × 5.1	Double (yellowish brown, yellowish white)
KMS1763	*Julie Eckersberg, née Juel, the Artist's Second Wife, 31.5 × 27.5*	1817	14.0 × 15.0	Single (white)
KMS4022	*Portrait of a Noblewoman Sophie Hedvig Løvenskiold and her Three-Year-Old Daughter, 62.5 × 51.5*	1817	12.2 × 13.7	Single (white)
KMS1241	*The Nathanson Family, 126.0 × 172.5*	1818	15.7 × 15.3	Single (white)
DHS111	*Portrait of the East India Merchant Albrecht Ludwig Schmidt, 156.7 × 98.3*	1818	16.1 × 11.7	Single (white)
DHS112	*Portrait of Frederikke Christiane Schmidt, 157.5 × 97.5*	1818	15.5 × 16.0	Not known
KMS724	*Princess Wilhelmine, Daughter of Frederik VI, 46.5 × 37.0*	1819	10.5 × 12.2	Single (white)
KMS3498	*Mendel Levin Nathanson's Elder Daughters, Bella and Hanna, 125.0 × 85.5*	1820	14.5 × 13.3	Single (white)
KMS4559	*Portrait of Emilie Henriette Massmann, Betrothed of Frederik Wilhelm Caspar von Benzon, 53.5 × 43.5*	1820	13.8 × 12.4	Single (white)
KMS1775	*Susanne Juel. The Artist's sister-in-Law, later to Become his Third Wife, 31.5 × 28.0*	1823	12.2 × 14.3	Single (white)
KMS1671	*A Russian Fleet at Anchor near Elsinore, 31.0 × 59.0*	1826	12.0 × 14.7	Single (white)
KMS8579	*Study of Clouds over the Sound, 20.5 × 32.3*	1826	11.8 × 13.8	Not known
KMS1664	*A Danish Corvette Laying in order to Confer with a Danish Brig: The Scene Being Set in West Indian Waters, 58.0 × 86.0*	1827	10.2 × 11.2	Not known
KMS608	*The Russian Ship of the Line 'Asow' and a Frigate at Anchor near Elsinore, 63.0 × 51.0*	1828	13.5 × 11.5	Single (white)
KMS6439	*A Corvette on the Stocks, 27.5 × 37.0*	1828	13.2 × 13.9	Single (white)
KMS1350	*Renbjærg Tileworks by Flensburg Fiord, 22.5 × 32.5*	1830	14.5 × 12.2	Single (white)
DHS Inv.nr.116	*View of Koster from the Ferry Pier at Kalvehave, 23.2 × 33.0*	1831	12.8 × 10.8	Not known
KMS255	*The 84-Gun Danish Warship 'Dronning Marie' in the Sound*	1834	13.0 × 12.0	Single (white)
KMS7284	*Langebro, Copenhagen, in the Moonlight with Running Figures, 45.5 × 33.5*	1836	Twill weave 16.3 × 21.0	Double (reddish brown, pale brown)
KS45	*Seated Male Nude, Peter Kristrup, 94.5 × 62.5*	1837	10.8 × 14.2	Not known
KS44	*Male Nude with Staff, Carl Frørup, 94.5 × 62.5*	1837	11.3 × 14.1	Not known
KMS1116	*The Corvette 'Galathea' in a Storm in the North Sea, 47.5 × 63.5*	1839	13.4 × 10.8	Double (yellowish, white)
KMS2011	*The Corvette 'Galathea' Lying to in order to Send Help to the Brig 'St Jean', 63.0 × 84.0*	1839	11.0 × 10.0	Double (reddish brown, white)
KMS3767	*A Privateer Outsailing a Pursuing Frigate, 55.5 × 68.5*	1845	14.3 × 13.8	Not known
KMS536	*Ships in the Sound North of Kronborg Castle, Elsinore, 39.5 × 50.0*	1847	13.9 × 13.6	Double (reddish brown, white)

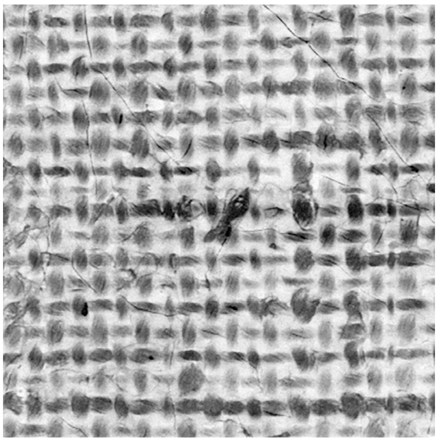

Figure 3. X-radiograph of the same area as in Figure 2 (SMK Photography; KADK/Mikkel Scharff image enhancement)

Figure 4. X-radiograph of Figure 3, processed with a Fourier filter using nip2 software, where the microcracks in the two directions are highlighted in red and orange. The crack propagations through the paint layers are not highlighted here (SMK Photography; KADK/Mikkel Scharff image enhancement)

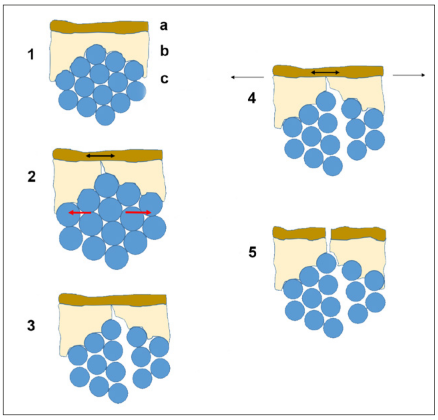

Figure 5. Schematic drawing of a cross-section of canvas thread and the superimposed layers, showing a step-by-step visualisation of microcrack creation and later propagation from ground layer(s) through superimposed layers: 1a) paint, 1b) ground, 1c) thread fibres; 2) moisture absorption causes the fibres to swell, resulting in cracking of the ground where it is thinnest; 3) dried fibres, the crack remains; 4) increased forces cause stress in the paint/second ground layer; 5) paint cracks (KADK/Cecil Krarup Andersen)

THE OCCURRENCE OF MICROCRACKS

Flax fibres swell significantly in diameter upon moisture exposure whereas swelling of the length is negligible. This means that swelling of the fibres at high relative humidity can cause local stress to be applied to a paint layer transverse to the individual fibres. A weaker, more hygroscopic lower ground layer may crack more readily. The assumed crack initiation process has been reconstructed in Figure 5.

The orientation of a crack is usually perpendicular to the orientation of the maximal stresses. For canvas paintings this would usually mean parallel to the edges of the painting. In this case, however, the underlying canvas clearly affects the orientation of the cracks. The cracks examined in this study were estimated, on average, to be 970 µm (~ 1.0 mm) long and 120 µm (~ 0.1 mm) wide at the thickest point, and invariably followed the twist and spinning degree of the fibres. Separation of the spun flax fibres requires forces lower than those needed to pull a single flax fibre to failure, which is why the cracks follow the direction of the fibres in the spun thread (Figure 6). The cracks are positioned where the ground layer is thinnest, i.e. above the crossover of two threads.

The direction of crack development depends on the direction of the principal stresses, but some lines of cracks in the examined paintings were seen to detour, incorporating the microcracks into a larger crack pattern. In cases where they were visible on the surface, the larger network of cracks was often shaped in a way suggesting that the microcracks in the ground had extended into the paint layer. In these cases, the stress accumulations at each end of the microcracks caused crack growth such that the microcracks became part of a larger crack network. Figure 7 illustrates this phenomenon.

CONCLUSION

The use of x-radiographs to examine the cracks on the surfaces of paintings by the Danish 19th-century painter C.W. Eckersberg enabled the detection of additional canvas-related microcracks in the ground layer in a number of the paintings. The findings indicated that swelling of the fibres in the canvas initiated the microcracks, particularly when weaker and more hygroscopic grounds were used, as seen in the layers containing earth pigments. These observations support the hypothesis that a hygroscopic substrate, such as wood or canvas, can affect the crack-building pattern in a painted surface. This paper highlighted the utility of x-radiographs in identifying such cracks, which are often hidden beneath paint layers, and presented a model for their initiation and potential propagation into the paint layers.

Studies of the paintings in historic collections may lead to the premature conclusion that their surfaces have reached the point of crack saturation and will therefore crack no further. Nevertheless, examination of ≤ 50 µm resolution x-radiographs can reveal microcracks in the ground structure and thereby a potential risk of further degradation. Increased tension due to certain conservation treatments or environmental changes exceeding historical fluctuations may present a risk of further crack growth into the paint layers of paintings showing microcracks. Conservation treatments likely to increase in-plane forces in the painting's structure, such as keying out or restretching, must therefore be carefully considered for paintings exhibiting microcracks.

The influence of historic environmental conditions is of course unknown as it is impossible to account for every environmental influence that a painting encountered. Nonetheless, further studies of microcracks in other groups of paintings will allow a better understanding of crack formation and lead to measures for its prevention.

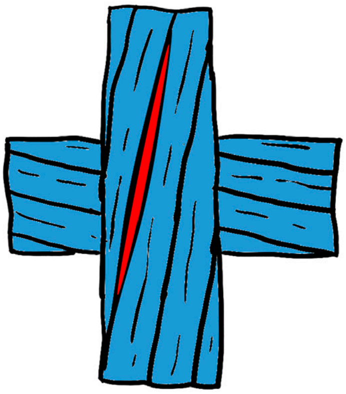

Figure 6. Schematic drawing of the point of intersection of two threads, at the top of which the ground layer is thinnest and the stress concentration strongest, causing crack formation. The crack thus formed is shown in red (KADK/Mikkel Scharff)

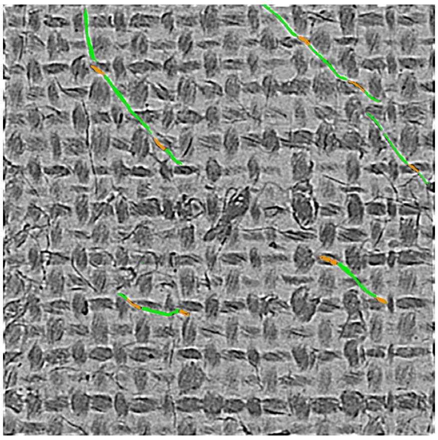

Figure 7. X-radiograph of Figure 3 processed with a Fourier filter in nip2, with further crack propagation/developement through the paint layers visualised with green (SMK Photography; KADK/Mikkel Scharff image enhancement)

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