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Use of hyperspectral imaging to monitor the effectiveness of plasma-generated atomic oxygen for non-contact cleaning of indigo dyed silk

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Abstract. This study explores the use of hyperspectral imaging (HSI) to monitor the effectiveness of plasma-generated atomic oxygen (AO) treatment for non-invasive cleaning of cultural heritage object. Silk samples dyed with indigo blue, including those soiled with soot to mimic historical artifacts, were treated with plasma-generated atomic oxygen for varying durations. Using HSI with a TWINS [1,2] birefringent interferometer, diffuse reflectance and light-induced fluorescence are observed. That allowed a precise evaluation of sample degradation avoiding any invasive sample extraction. This research not only contributes to the field of cultural heritage conservation but also enhances understanding of indigo colour degradation processes and the evaluation of non-invasive cleaning techniques on sensitive materials.

1 Introduction

The importance of cleaning and restoring cultural artifacts with minimal harm to their integrity is widely acknowledged. For this reason, plasma-generated atomic oxygen cleaning has emerged as a promising approach for various cultural heritage items, offering a non-invasive alternative to more traditional cleaning process [3]. However, studies are needed to determine the optimal plasma treatment parameters to achieve cleanliness of the artifact without causing any chemical and morphological alteration.

In this context, an additional goal is to identify optimal non-invasive techniques that can inform the effect of cleaning. In this research, we propose the use of hyperspectral imaging (HSI) to monitor the effectiveness of atmospheric plasma-generated atomic oxygen (AO) for non-contact cleaning of dyed silk and to assess potential degradation induced by the cleaning treatment. Specifically, HSI is implemented to sequentially study diffuse reflectance and light-induced fluorescence of samples, achieving multi-modal information.

The focus is on indigo blue, which can be considered both a pigment and a dye as it is an insoluble organic compound. Traditionally, indigo, is extracted from various plants, most of them of genus *Indigofera* [4].

In the past, a multispectral study was conducted on indigo-dyed samples to obtain degradation classes based on the degree of dye deterioration under stress conditions [5]. The novelty of this study lies in the high spectral resolution of our set-up and in the combination of reflectance and fluorescence spectral information of samples that may enable a more complete chemical and physical understanding of indigo degradation.

2 Materials and methods

Silk samples dyed with natural indigo were utilized for experimentation (Figure 1). The samples were made to assess the efficacy of plasma-generated atomic oxygen treatment on delicate surfaces prior to its application on culturally significant objects. Specifically, there are two sets of silk replicas dyed with indigo, each treated with AO for 10, 20 and 40 minutes. Additionally, there are two sets of indigo-dyed silk replicas deliberately soiled with a standardized sooting methodology to imitate fire-damaged historical textiles, also subjected to plasma treatment for 10, 20 and 40 minutes.

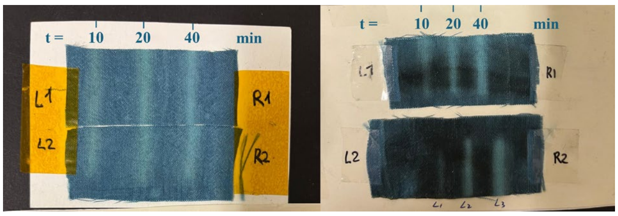

Fig. 1. The replicas of silk fabric dyed with indigo. On the right, replicas treated with plasma-generated atomic oxygen for 10, 20 and 40 minutes. On the left, replicas soiled with soot and treated with plasma for 10, 20 and 40 minutes.

The AO system applied in Gent University uses 4 slm (standard litre per minute) He as shielding gas, 4 slm He and O_2-He 60 sccm (standard cubic centimeters per minute) as main gases, power range of 5.5 to 6.1 W, at 4 mm distance from the nozzle.

Hyperspectral analyses were conducted with a hyperspectral camera based on the TWINS [1,2] birefringent interferometer, by collecting diffuse

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reflectance and fluorescence spectral datacube in the spectral range 400-1000 nm (VIS-NIR spectral region).

Samples were analysed either using a "macro" collection optics, which through inspection of a 1-cm square area of lateral dimension, achieves sub-millimeter spatial resolution, or with a wider field-of-view collection scheme, which allows imaging of all replicas together and allows better comparison of the effects of different treatment times.

3 Preliminary results and discussion

The first noticeable observation, even by eye, is that the reflectance increases as the number of minutes of cleaning increases, as we can see in Figure 2. In shorter treatments, it may remove black dirt as the spectrum is close to the reference of indigo-dye silk untreated and unsooted. Later the treatment creates fading of the indigo as the spectrum in the 430-500 nm range exceeds that of the reference.

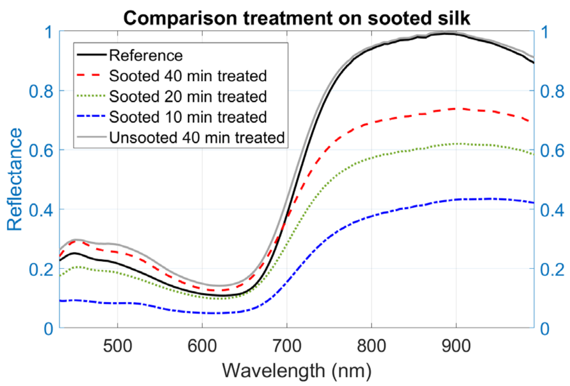

Fig. 2. Reflectance spectra of indigo-dye silk in correspondence of areas with unsooted silk, sooted silk and sooted silk subjected to different plasma cleaning.

Starting from diffuse reflectance spectral data, it is useful to retrieve pseudo absorbance spectral data. In the case of opaque samples as the ones analysed in the present research, where the effects of light scattering cannot be neglected, pseudo-absorbance is estimated considering the approximate model of the Kubelka-Munk two-stream theory [6] as the KM factor:

$$KM(\lambda) = \frac{1-R(\lambda)^2}{2R(\lambda)} \quad (1)$$

where R(λ) is the diffuse reflectance spectra of an opaque sample.

Looking at the pseudo-absorbance spectra (Figure 3), it is observed that there is no spectral shift of the absorbance maximum following AO treatment, which was believed to indicate a reduction in the degree of conjugation from indigo to its degradation products [7]. Furthermore, as the treatment time increases, there is a lowering of the absorption maximum at 630 nm. This gradual change in the spectrum suggests an increase in the presence of his degradation products, such as dehydroindigo and isatin [4].

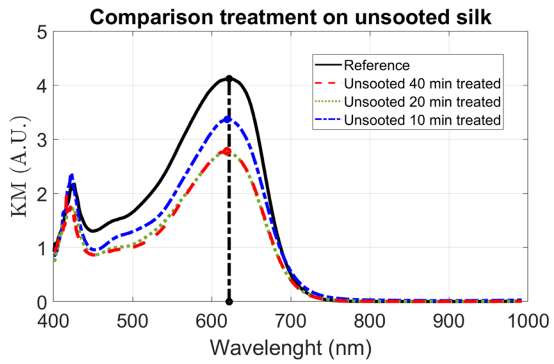

Fig. 3. Pseudo-absorbance (quoted as KM, following application of the Kubelka-Munk model to diffuse reflectance data) spectra of indigo-dyed silk untreated and treated with plasma treatment for 10, 20 and 40 minutes.

4 Conclusion

In conclusion, this study demonstrates the potential of hyperspectral imaging to estimate the effectiveness of plasma-generated atomic oxygen treatment for non-contact cleaning of dyed silk. The preliminary results suggest that plasma treatment can effectively remove dirt while minimizing colour damage if the duration of the treatment is not too long.

Research will be complemented with results from fluorescence hyperspectral imaging to achieve a thorough chemical and physical understanding of the effects of AO treatment on dyed silk fabrics.

References

1. D. Brida, C. Manzoni, and G. Cerullo, Opt. Lett. **37**, 3027 (2012)
2. A. Perri, B.E.N. De Faria, D.C. Teles-Ferreira, D. Comelli, G. Valentini, F. Preda, D. Polli, A. Paula, G. Cerullo, and C. Manzoni, Opt. Express **27**, 15956 (2019)
3. R. Jiao, F. Sun, S. Zeng, and J. Li, J. Cult. Herit. **63**, 240 (2023)
4. N. Tello-Burgos, A. López-Montes, J. Ballesta-Claver, F. J. C. Montero, and M. Del Rosario Blanc García, Stud. Conserv. **66**, 7 (2020)
5. N. T. Burgos, A. López-Montes, E. M. Valero, J. L. Nieves, and M. R. Blanc, Color Res. Appl. **47**, 486 (2021)
6. L. Rahmawati, A. M. Zahra, R. Listanti, R. E. Masithoh, H. Hariadi, N. Adnan, M. I. Syafutri, E. Lidiasari, R. Z. Amdani, N. Puspitahati, S. Agustini, L. Nuraini, S. D. Volkandari, M. F. Karimy, N. Suratno, A. Windarsih, and M. F. R. Pahlawan, Food Sci. Technol. Int. **43**, (2023)
7. X. Zhou, Y. Guo, L. Shi, Q. Han, C. Lin, L. Zhang, M. Wu, and W. Zhang, Dyes Pigments **218**, 111455 (2023)