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Multimodal analysis reveals hydrolysis as a shared mechanism in magnetic tape degradation

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Magnetic tape degradation threatens large portions of twentieth-century audiovisual heritage preserved in archives worldwide. Degraded tapes are commonly classified by their behaviour during playback, but the relationship between these macroscopic symptoms and the underlying chemical degradation processes remains unclear. Here we investigate degraded magnetic tapes using a multimodal analytical approach combining infrared spectroscopy, optical microscopy, and scanning electron microscopy. Tapes previously diagnosed with different binder degradation issues exhibit infrared signatures associated with poly(ester-urethane) binder hydrolysis that are reduced by heat treatment, but surface morphology differences govern the macroscopic behaviour of the tapes. These results show that several forms of tape degradation result from a common chemical process, while explaining differences in observed failure mode and remediation approaches. They motivate reinterpretation of tape degradation classifications in terms of underlying chemical and microscopic origins. We also demonstrate the importance of multimodal diagnostics for reliable assessment and targeted remediation of magnetic audiovisual tapes.

Magnetic tape was the dominant medium for professional audio and video recording from the 1950s through the early 2000s and remains a critical carrier of twentieth-century cultural heritage [https://www.iasa-web.org/magnetic-tape-alert-project]. Large archival collections worldwide contain unique recordings stored on magnetic tape. As these tapes age, they suffer from wear and chemical decay that can make them fragile and even unplayable[1,2].

Magnetic audio tape typically consists of three main layers, shown schematically in (Fig. 1a)[2–4]. The top magnetic layer is made of micron-sized magnetic pigment, most commonly gamma ferric oxide (γ-Fe_2O_3) but sometimes magnetite (Fe_3O_4), chromate (CrO_2), and other magnetic materials. These particles are embedded in a polymer binder, typically polyester-polyurethane (PE-PU). This layer can also contain other materials such as lubricants and abrasives. The base layer is typically made of plastic, such as cellulose acetate, polyvinyl chloride (PVC), or polyethylene terephthalate (PET), with the latter being the most common in archived magnetic audio tapes. Additionally, some tapes include a thin back coating, typically carbon black in a similar PE-PU binder, that aids tape packing through reducing inter-layer entrained air and static charge.

Magnetic tapes can suffer from a wide array of degradation issues, which are typically classified based on their response to playback and remediation approaches[1,2,5]. Differing syndrome classifications link condition and generally successful remediation techniques and are useful for the restoration engineer. This scheme is, however, imprecise from the perspective of scientific analysis to define the failure mechanisms that result in the current condition of a tape. One major degradation class is soft binder syndrome (SBS), which is used as a broad umbrella term to cover all failure modes relating to binder breakdown (potentially in the magnetic layer and/or the back coat)[6]. In this framework, sticky-shed syndrome (SSS) is by far the most common sub-category and describes tapes with a sticky surface that deposits residue on tape guides and playback heads but becomes temporarily playable after thermal treatment ('baking')[7,8]. Other tapes grouped under SBS show different behaviours that are not necessarily resolved by baking, such as strong interlayer adhesion, squealing caused by stick-slip, magnetic layer shedding, or accumulation of residue during playback[5,9–12]. As a result, current classifications are largely based on phenomenological observations made during tape handling, remediation, and playback, rather than on direct identification of the underlying degradation

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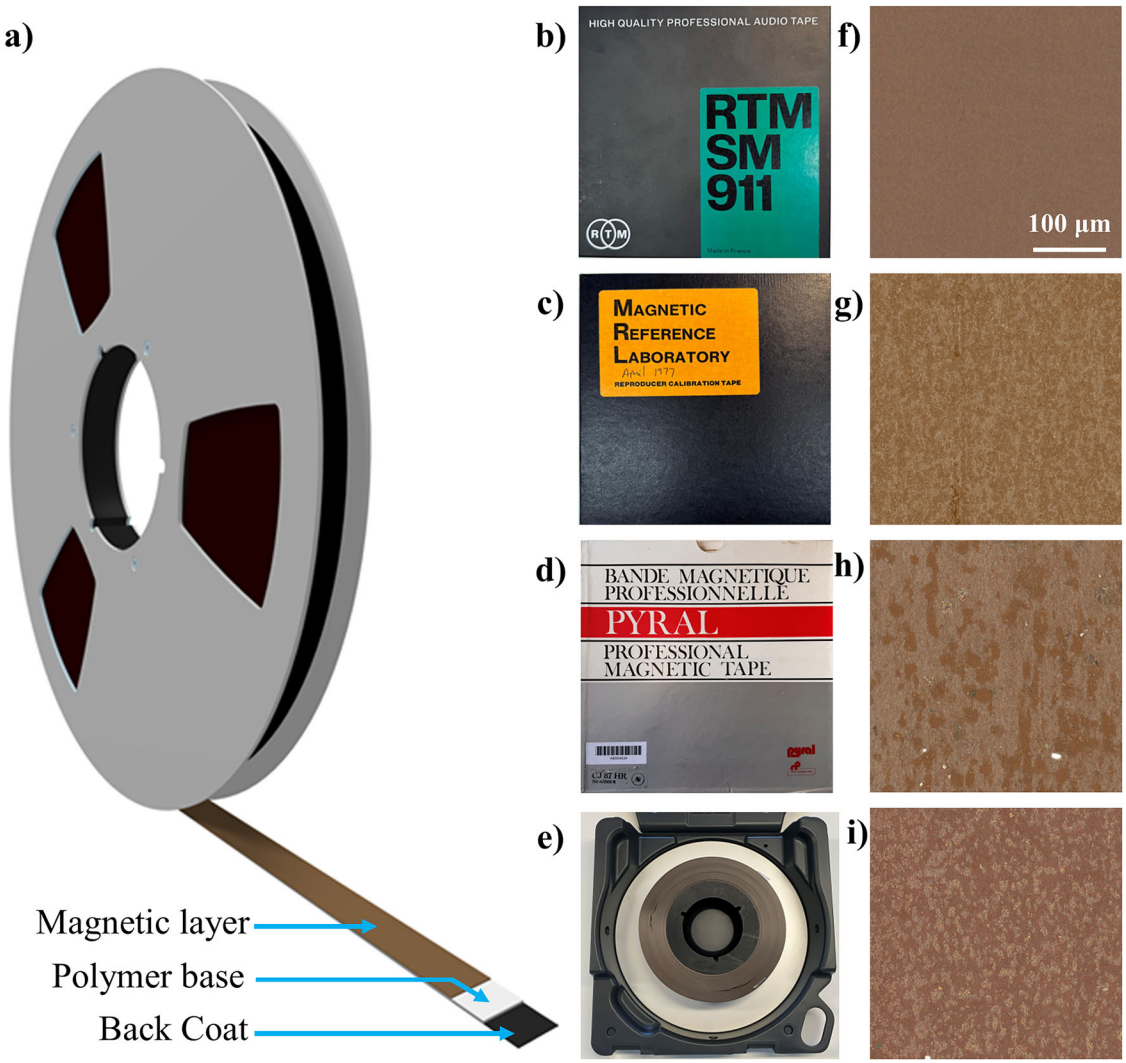


Fig. 1 | a Schematic of the different layers that comprise a standard audio tape. **b**–**e** Images of the cases of the four tapes studied and (**f**–**i**) High-resolution optical microscopy images at 2000x magnification: (**b**, **f**) RTM SM911, (**c**, **g**) ¼″ Ampex 406, (**d**, **h**) Pyral CJ87, and (**e**, **i**) 2″ Ampex 456.

mechanism. A measurement-based framework is therefore needed to distinguish the microscopic and chemical origins of degradation in tapes currently grouped under SBS in order to provide a sound basis for recommending a specific remediation technique in order to best preserve both the tape and the fidelity of its recording[13].

The chemical degradation of the binder holding the magnetic particles is widely recognized as the main cause for SSS[1,14–16]. In particular, hydrolysis of PE-PU binders leads to chain scission and the formation of lower-molecular-weight species that alter the mechanical and tribological properties of the magnetic coating[3]. A common remediation approach for tapes affected by binder hydrolysis is heat treatment, which temporarily restores playability by removing absorbed moisture and modifying the physical state of the binder[8]. However, in practice this treatment does not always succeed, and some tapes do not recover playability after baking[1,6,9,10,17,18].

Recently, attenuated total reflection Fourier-transform infrared spectroscopy (ATR-FTIR) has proven particularly useful for identifying spectral features associated with SSS tapes, which are directly connected to hydrolysis, with high reliability[19–22]. However, many investigations rely primarily on a single analytical technique and focus only on this degradation phenomenon. As a result, the relationship between chemical degradation processes, microscopic structural changes, and the diverse macroscopic behaviours observed during playback remains incompletely understood, thereby hindering the development of a clear mechanism-based classification framework based on material diagnostics. Furthermore, there are inconsistencies between ATR-FTIR studies of hydrolysis in pure PE-PU compared to what is observed in degraded magnetic tapes that needs understanding[19–24].

In this work, we investigate degraded magnetic tapes using a multimodal analytical approach combining ATR-FTIR spectroscopy, optical microscopy, and scanning electron microscopy (SEM). By correlating chemical signatures with microscopic morphology, we examine tapes that have previously been diagnosed with different forms of SBS, including SSS and other issues unique to specific tape models. We find that they exhibit infrared signatures of SSS typically assigned to PE-PU binder hydrolysis, indicating a shared underlying chemical origin across these macroscopically distinct degradation phenomena. We further examine the spatial distribution of these infrared signatures across the tape surface and investigate the effects of heat treatment on the chemical and morphological properties of degraded tapes. Together, these observations provide insight into the relationship between chemical degradation, microscopic structure, and the practical behaviour of tapes during remediation and playback. We link these ATR-FTIR signatures to the short-segment ester products of binder hydrolysis, based on literature. Microscopy further reveals strong morphological differences and spatially heterogeneous degradation, while showing that heat treatment can reduce SSS signatures even in tapes that remain unplayable. In particular, we confirm that transfer of back-coat

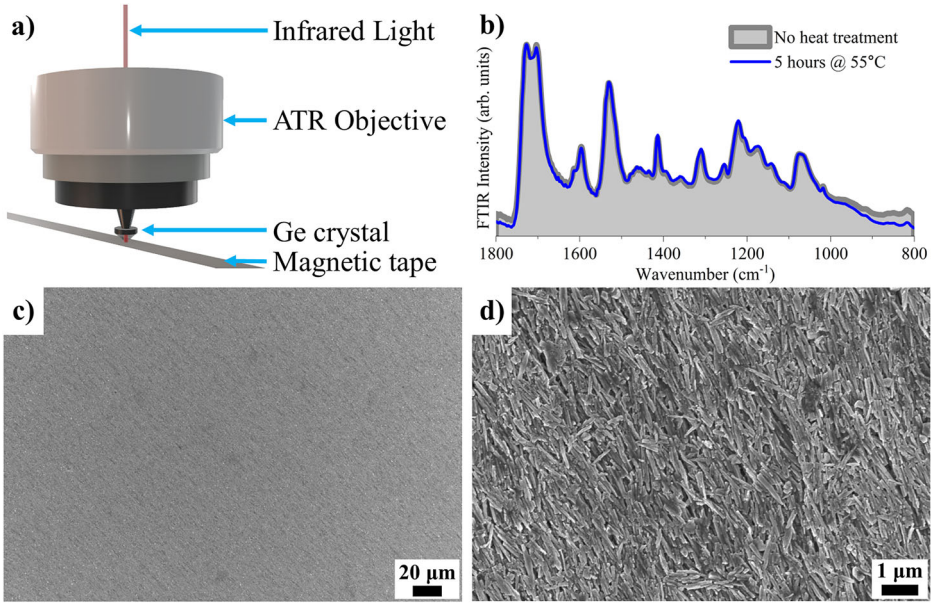


Fig. 2 | a Schematic of ATR-FTIR measurement setup. **b** ATR-FTIR spectra taken on a new RTM tape both in its original state (grey curve) and after a 5-hour heat treatment at 55 °C (blue curve). **c**, **d** SEM images taken on the untreated tape at (**c**) 1,000x and (**d**) 30,000x magnifications.

material constitutes an additional degradation process that plays a major role in Pyral CJ87 tapes, rendering heat treatment alone insufficient to restore playability. Based on these results, we discuss a revised model of tape degradation informed by our measurements and show how this can be used to design tailored conservation and remediation workflows. Overall, our results indicate that a single analysis technique is insufficient for tape diagnosis and that a multimodal approach is necessary.

Methods

Tapes investigated

We investigated four main γ-Fe_2O_3 analogue audio tapes; one healthy reference and three degraded tapes each previously diagnosed with different issues under the broad category of SBS. A new ¼″ *Recording The Masters* (RTM) SM911 tape from 2021 was used as the reference healthy tape. A ¼″ *Ampex 406 Magnetic Reference Laboratory* (MRL) tape from 1977 represents a severe case of SSS, with the delamination of large chunks of the magnetic coating that occurred while the tape was being unwound. We also studied a 2″ *Ampex 456* tape that remained sealed since manufacture in 1994 and is believed to represent a milder form of SSS. This tape clearly sticks while unwinding; a thin layer of the magnetic coating adheres to the back of the adjacent tape layer. Such 2″ tapes only partially respond to baking, with stickiness and delamination persisting towards the centre of the pack even after long baking times. Finally, we investigate a *Pyral CJ87* tape from ca. 1979 that produces a black residue upon playback but is not sticky and does not recover playability through baking alone[10]. Professional audio tapes typically comprise a magnetic layer approximately 10–15 µm thick, a polyester base of around 35 µm, and a back coat approximately 1–2 µm thick, although the exact layer thicknesses vary among tape formulations. For each tape, several small segments (a few cm) were taken for the different experiments and heat treatments.

Infrared spectroscopy

ATR-FTIR measurements were carried out using a Bruker Vertex 80 V FTIR spectrometer coupled to a Hyperion 3000 microscope equipped with a liquid nitrogen cooled single-element MCT (HgCdTe) detector. We used a 20x attenuated total reflection (ATR) objective with a 100 µm footprint Ge crystal. During measurement, the crystal is pressed on to the samples with a contact pressure of 0.5 N. The IR source is a heated SiC bar (globar - mid infrared from 4000 to 500 cm^{-1}) for sample illumination. The depth of penetration of IR light into the sample when using our ATR crystal, with a refractive index around 1.5, is up to 2 µm. Spectra were acquired in reflection mode over the range 4000–600 cm^{-1} (wavelengths 2.5–16.7 µm) with a spectral resolution of 2 cm^{-1} and 64 scans at 40 Hz. Atmospheric contributions and instrumental background were removed using a reference spectrum without a sample present.

Scanning electron microscopy (SEM)

Electron microscopy images were collected using a Zeiss Supra 55VP with 4 keV incident energy and at 4 mm working distance using the in-lens detector to collect backscattered electrons. The tape samples were mounted on standard SEM stubs placed at normal incidence to the electron beam. The chamber vacuum was better than 5×10^{-5} mbar.

Optical microscopy

Low-magnification optical images of tape surfaces were taken with a Keyence VK-X 31,000 microscope equipped with 2.5x−150x objectives. High-magnification images in Fig. 1f–i were taken with a Keyence VHX-7000N digital microscope equipped with 20x-7000x objectives at the TwinMic beamline, Elettra Sincrotrone Trieste[25].

Heat treatment

The heat treatments were performed using a SalvisLab Thermocenter TC100 sample preparation oven. Tape segments ca. 10 cm in length were wound loosely around a glass beaker and taped on each end to allow for sufficient air flow around the entirety of the segment. The temperature was ramped from 25 °C to 55 °C at a rate of 0.5 °C per minute, then held at this temperature for a fixed time, before being reduced to 25 °C at 2 °C per minute. The temperature was stable to within 0.1 °C of the set temperature for the duration of the holding time. The internal fan of the oven operated at 100% throughout the process, ensuring constant airflow to the tapes. Heating while imaging (see Suppl. Note 1) was done with a custom Peltier heater powered with a RND 320-KWR103 programmable DC power supply and the temperature was monitored with a Pt100 thermocouple placed on the heater next to the tape.

Results

New RTM tape

As a control, we investigated a newly produced RTM tape. We performed both IR spectroscopy and SEM imaging on a pristine segment of the tape and one that had undergone a heat treatment at 55 °C for 5 h following the procedure outlined above. From the IR spectra (Fig. 2a), the heat treatment has no effect on the chemical composition. High-resolution optical images

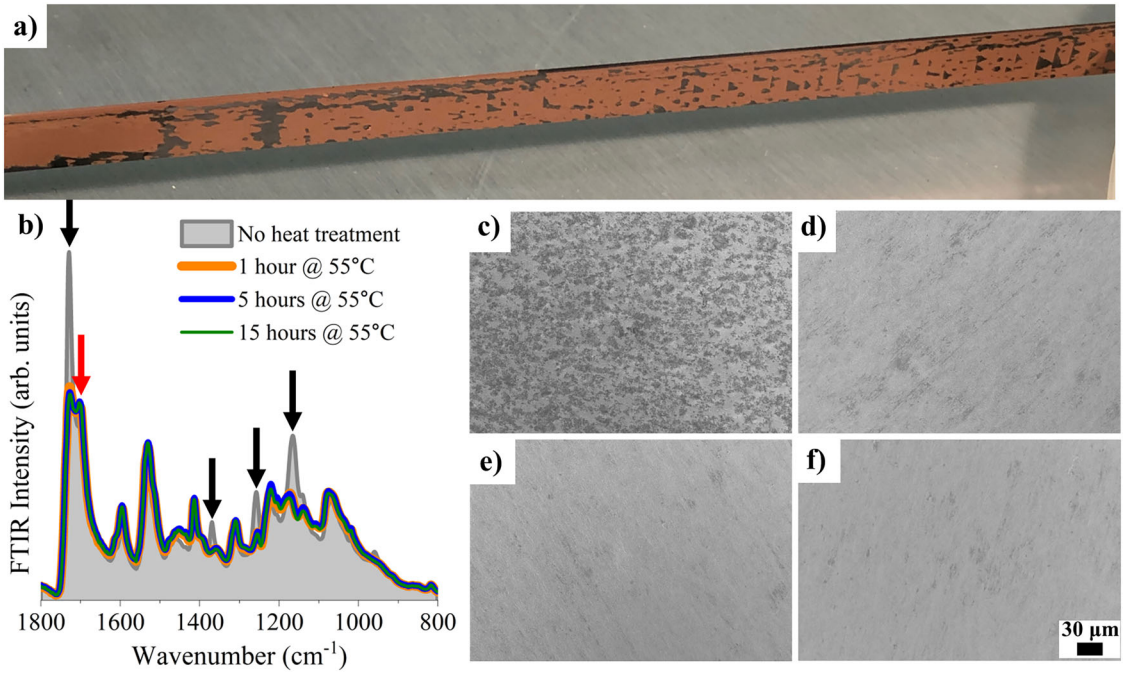


Fig. 3 | a Image of strong delamination observed whilst unwinding ¼″ Ampex 406 tape with severe SSS. **b** ATR-FTIR spectra of ¼″ Ampex 406 tape segments with SSS in the initial untreated state and after heat treatments of different lengths, measured on non-delaminated regions. The black/red arrows are peaks that are stronger/weaker in tapes with SSS identified in previous works[1,19–21]. **c**–**f** SEM images at 1000x magnification of the same tape segments: (**c**) untreated, (**d**) 1 h at 55 °C, (**e**) 5 h at 55 °C, and (**f**) 15 h at 55 °C.

(Fig. 1f) and SEM images (Fig. 2b, c) show a clean tape surface both before and after heat treatment, with the magnetic grains clearly visible in the SEM at higher magnifications.

Sticky-Shed syndrome

We performed heat treatment at 55 °C on three different segments of the degraded ¼″ Ampex 406 tape for 1, 5, and 15 hours following the procedure outlined in the methods. We then performed IR and SEM measurements on each segment to study the effect of heat treatment on this tape diagnosed with a standard case of SSS with severe delamination close to the hub (Fig. 3a). The IR spectrum from the untreated segment shows the same spectral fingerprints found to be characteristic of tapes with SSS e.g., in refs. 19–21, marked with arrows in Fig. 3b. All three segments treated for different lengths of time show a reduction of these characteristic spectral features, regardless of treatment time, as illustrated by the overlapping curves. In fact, we find that the chemical change in the tape occurs at around 45 °C and is very rapid, within seconds, and with minimal additional changes beyond a few minutes. To illustrate this, we present both a set of IR measurements taken at different temperatures and a movie of the tape surface as a function of temperature in Suppl. Fig. 1 and the Supplementary Movie.

This analysis is further supported by our SEM images of the tape segments. As can be seen in Fig. 3c–f, the untreated tape has a highly textured surface, with a large number of dark puddles. These are low molecular weight segments of the soft polyester binder released during the hydrolysis process[7,15,16,20]. These almost completely vanish after heat treatment for one hour, confirming the IR spectroscopy measurements indicating that the effects of heat treatment on the tape are rapid.

Given that the tape itself starts to chemically change within seconds and that IR spectroscopy indicates it is playable after baking for an hour, why do so many tapes require long baking times (on the order of 8 h to days) to become playable? Our results support the general consensus that this is due to the packing of the tape on the reel[1,26]. Indeed, the predominant explanation for the efficacy of heat treatment for remediating tapes suffering from SSS is the removal of water from the tape pack, causing at least a partial recombination of the shorter polymer chains[7,8,27], although other explanations have been proposed[9,14]. A previous study on heat treatment for full 1″ tape reels found that thermal diffusion occurs on a timescale of a few hours, whereas hygroscopic equilibrium requires several days[28]. Therefore, in a full reel, moisture diffusion occurs ca. 50 times slower than the thermal diffusion into the tape pack or the nominal rate of polymer recombination. This limits the rate at which the polymer recombination can occur, particularly closer to the pack centre, and explains the much longer timescales required for successful heat treatment for full tape reels. It has also been suggested that the relatively hygroscopic carbon black back-coat retains more moisture during heat treatment and can initiate the redegradation of the binder when packed onto a reel[1,27]. We also believe this is the cause of tape reels re-degrading relatively quickly after heat treatment, often becoming unplayable within a couple of weeks, compared to short tape segments. We found that our baked segments showed no noticeable signs of redegradation after 18 months of storage in standard laboratory conditions when they are not spooled on a reel (see Suppl. Fig. 5).

To probe this further, we took a set of ATR-FTIR spectra across the width of the unbaked ¼″ Ampex 406 tape, shown in Fig. 4a. Three example spectra are shown in Fig. 4b, demonstrating clear variations at different positions on the tape, particularly in the fingerprint peaks for SSS. Furthermore, in Fig. 4c we plot the ratio of the two primary (highest wavenumber) peaks, which are stronger (black arrow) and weaker (red arrow) on tapes with SSS respectively. This shows larger variations in the degree of SSS towards the edges of the tape, with a more consistent level of degradation at the tape centre. We also note that the tape edges are where the majority of the delamination of the magnetic layer is observed on this tape (Fig. 3a), close to the hub, which reflects findings in other similar tapes. This emphasises the need for more systematic measurements of tapes for diagnostic purposes, as spatial inhomogeneity is an important concern and could potentially lead to a misdiagnosis. Our ATR-FTIR is equipped with a microscope in the optical path, and the tape surface can be inspected both before and after IR measurements (see Suppl. Fig. 3). This can be used to identify regions with different levels of degradation, as the surface residue of binder hydrolysis is often visible under a microscope (Fig. 1g), aiding the diagnosis beyond single-point ATR-FTIR spectra.

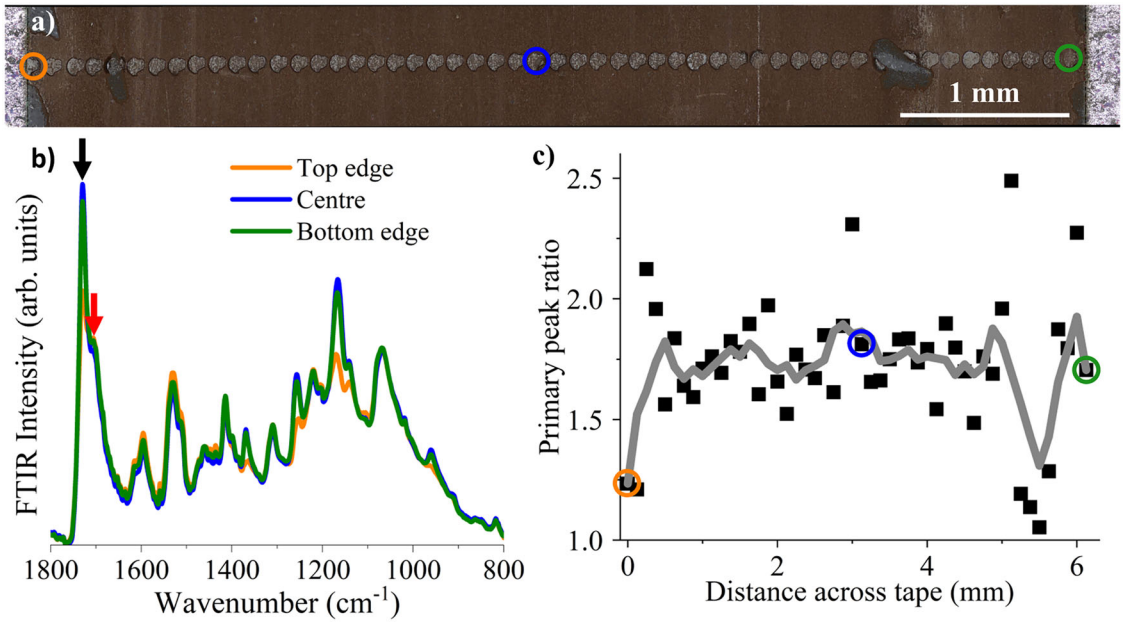
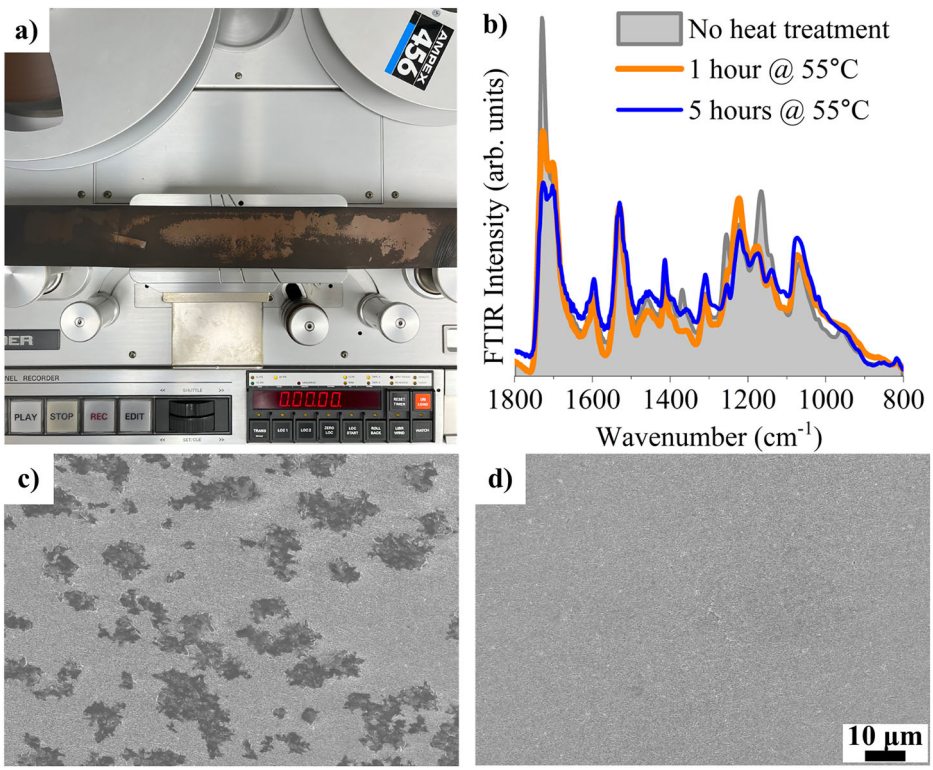


Fig. 4 | a Optical image across the width of a ¼″ Ampex 406 tape segment, showing the locations for the set of positional ATR-FTIR measurements from the imprints of the 100 µm Ge crystal. The white scale bar is 1 mm. **b** ATR-FTIR spectra at three different positions across the width of a segment of the same ¼″ Ampex 406 tape as in Fig. 3, marked by correspondingly coloured circles in (**a**, **c**). Two primary peaks indicative of SSS are marked by black and red arrows. **c** Ratio of the marked primary peaks as a function of distance across the width of the tape measured every 125 µm. The grey curve is a five-point moving average filter, emphasising that the largest variations occur at the edge of the tape.

Fig. 5 | a Image of 2″ Ampex 456 tape back coat showing the delamination of the magnetic coating. **b** ATR-FTIR spectra of 2″ Ampex 456 tape segments in the initial untreated state and after heat treatments of different lengths. **c**, **d** SEM images at 1000x magnification of the same tape segments: (**c**) untreated and (**d**) after 5 h at 55 °C.



Additionally, we conducted similar investigations on segments of the 2″ Ampex 456 tape, which shows mild adhesion and surface delamination when unwound (Fig. 5a). Tapes like this partially respond to heat treatment, although often require very long treatment times to become playable and even then cannot be read to the core. IR spectroscopy measurements and SEM imaging were performed on a small segment of the tape near the middle of the reel where adhesion was first observed (Fig. 5b–d). These show the same spectral signatures as typical SSS that result from binder hydrolysis (Fig. 3). We did observe, however, an inhomogeneous distribution of SSS signatures correlated with clear optical symptoms of binder hydrolysis (Supplementary Fig. S2, S3). The inhomogeneous degradation could be caused by the pressure distribution in the wound reel, for example due to

trapped air pockets. Areas with a higher density of short-chain ester patches will have stronger interlayer adhesion and cause the partial delamination of the magnetic coating in that region. This highlights the autocatalytic nature of the binder hydrolysis process[8,15,29] and the need for comprehensive investigations of a given tape rather than single-point measurements. Furthermore, these small segments also respond to heat treatment very rapidly, as with conventional SSS. The fact that larger 2″ tapes typically require much longer heat treatment times compared to ¼″ tapes is again further evidence that the packing of the tapes onto the reels and subsequent limitation on the moisture diffusion rate[28] is the relevant difference explaining the long baking times required in many situations.

Pyral tape

We next investigated segments of a Pyral CJ87 tape, whose degradation behaviour has been discussed within the broader SBS category[10]. These tapes deposit large amounts of black residue on play heads and guides during playback, preventing digitization beyond a few seconds. They are not sticky, do not recover playability through baking alone, and are therefore not considered as a typical manifestation of SSS. We performed heat treatment on segments of this tape at 55 °C for 5, 15, and 72 h following the procedure outlined in the methods section, followed by IR and SEM measurements on each segment to study the effect of heat treatment on this tape. As seen in Fig. 6, this tape shows the same spectral fingerprints as conventional SSS (see Fig. 3b). Furthermore, these fingerprint peaks respond to heat treatment in the same manner as conventional SSS, with a rapid initial reduction followed by more gradual changes during extended baking. This suggests that binder hydrolysis is also a key component of the degradation in this tape, but that the associated spectral features are reduced on longer timescales compared to conventional SSS.

SEM images of the untreated segment show larger puddles on the tape surface than the other degraded tapes. Furthermore, one can clearly see that, after all but the longest heat treatments, these puddles weaken but do not entirely vanish in the same way as with the ¼″ Ampex 406 tape. These are the black back coat residue deposited on the tape player. The longer treatment times causes this residue to partially 'melt' into the binder, reducing the surface contamination but not removing it entirely. This supports the conclusion that the tape is not rendered playable within reasonable timescales through heat treatment alone: it takes ca. 72 h for the surface of even these isolated tape segments, unconstrained by the surrounding reel pack, to look relatively 'clean'.

Reference [10] proposed that this residue arises from transfer of back-coat material to the adjacent magnetic layer, and our results confirm this interpretation. In addition to the standard SSS features, the Pyral tape shows an additional peak in the IR spectra that is not observed in the other tapes, marked by a black arrow in Fig. 6a. This peak matches a feature observed in the IR spectrum of the tape's back coat (Supplementary Fig 4), indicating that transferred back-coat material is indeed present on the magnetic surface. The IR spectra of the back coat also show SSS fingerprint peaks that reduce upon baking, like the magnetic layer. These observations are consistent with binder degradation of both the magnetic and back coat layers, which promotes adhesion between adjacent tape layers. As a result, back-coat material is transferred onto the magnetic surface and forms residue on the tape path during playback attempts. While the short-chain ester segments from the degraded binder respond to heat treatment in the standard way, the transferred back-coat material (carbon black) remains on the surface even after extended heating. This explains why heat treatment alone is insufficient: the remediation workflow must be supplemented with cleaning to remove back-coat residue and render these tapes temporarily playable, as described in ref 10.

Discussion

PE-PU binders are comprised of flexible polyester soft-segments and rigid polyurethane hard-segments, with the soft-segment significantly more susceptible to hydrolysis compared to the hard segment[7,15,16,23,24]. In FTIR measurements of PE-PU, the 1728 cm^{-1} peak corresponds to the C = O bond in the soft segment and the 1702 cm^{-1} peak is due to the equivalent C = O bond in the hard segment[21,23,24]. In dedicated studies of PE-PU hydrolysis with FTIR[23,24], the behaviour of these two principal peaks is inverted compared to what is observed for tapes with SSS[19–22], i.e., the 1728 cm^{-1} peak *decreases* and the 1709 cm^{-1} peak *increases* in more hydrolysed samples. This discrepancy warrants discussion here.

In the hydrolysis process the cleaved ester linkages cause the soft binder segments to form low molecular weight chains, which can migrate to the surface of the tape[20]. It was demonstrated by solvent extraction tests and IR spectroscopy that the removed content contains only polyester segments[7,15,16]. As ATR-FTIR primarily probes the surface of the tape (approximately 2 µm), it is then sensible that the spectra on SSS tapes show an increase in the proportion of soft-segment ester C = O bonds compared to hard segment C = O bonds. Therefore, the change in peak ratios is not representative of the degradation of the ester bond, which leads to the spectral changes observed in pure PE-PU[23,24], but rather a change in the relative concentration of the short and hard segments at the tape surface. It is clear from measurements on the 2″ Ampex 456 tape that the strength of the SSS signatures depends directly on the local concentration of dark puddles viewed by optical microscopy, thereby demonstrating that these are puddles of short-chain ester segments. Furthermore, as shown in Suppl. Fig. 8, these

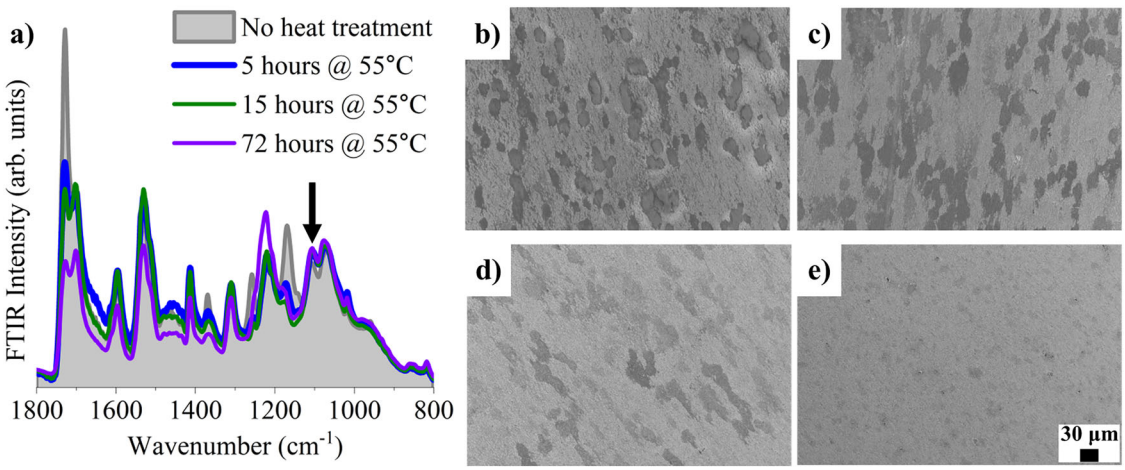


Fig. 6 | a ATR-FTIR spectra of Pyral CJ87 tape segments in the initial untreated state and after heat treatments of different lengths. The peak that is absent from spectra on other tapes is consistent with back-coat material and is marked with a black arrow. **b**–**e** SEM images at 1000x magnification of the same tape segments: (**b**) untreated, (**c**) 5 h at 55 °C, (d) 15 h at 55 °C, and (**e**) 72 h at 55 °C.

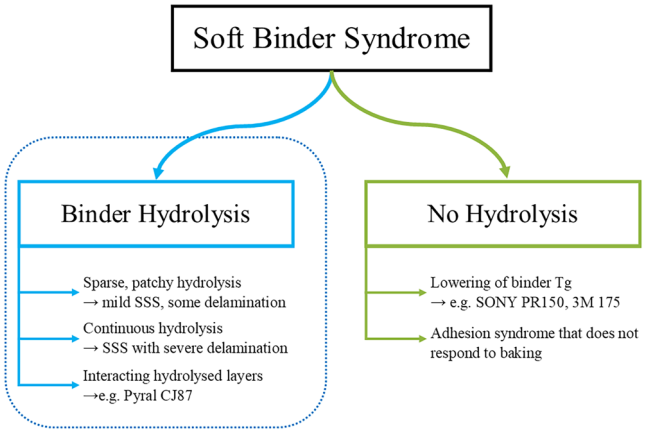


Fig. 7 | Schematic of our proposed classification of degradation conditions under the umbrella of SBS. This work focuses on the study of tapes within the 'binder hydrolysis' sub-category (blue dashed box).

puddles have a typical height ca 0.5 µm, thereby constituting a significant proportion of the ATR probing depth. Thus, for magnetic tape degradation, ATR-FTIR is primarily probing the change in chemical distribution resulting from binder hydrolysis, in line with the literature.

Our results indicate that several commonly observed tape binder degradation behaviours share a common underlying chemical origin and exhibit infrared spectral features associated with polyester soft-segment byproducts of binder hydrolysis. These decrease rapidly during heating, consistent with removal of absorbed moisture and the migration of these short-chain products back into the tape bulk, but not necessarily evidence of any polymer recombination. However, this surface reduction in ester spectral signatures does not necessarily mean that the tape is playable again or that the tape surface fully recovers. While ATR-FTIR provides valuable information about the chemical state of the binder surface, it does not necessarily capture physical changes. Microscopy therefore plays a crucial complementary role by revealing structural features that directly influence tape behaviour during handling and playback. This is particularly important for tapes such as the Pyral CJ87, where ATR-FTIR analysis of segments after heat treatment suggests they should be playable. This technique alone does not address transferred back-coat material from the magnetic surface, which must be complemented by cleaning to enable playback[10]. Additionally, ATR-FTIR of the back coats of the tapes distinguishes those for which back coat hydrolysis also contributes to the degradation (Pyral CJ87, Suppl. Fig. 4) and those for which it does not (¼" Ampex 406 and 2″ Ampex 456, Suppl. Fig. 7).

These findings have practical implications for conservation. From macroscopic observations of the tape properties (stickiness, adhesion etc.), potential treatment pathways can be identified utilising a combination of ATR-FTIR, SEM, and optical microscopy. Crucially, these investigations can be performed on very small segments of tape (~ 1 cm), such that a section of a problematic tape can be tested to understand whether heat treatment alone would be sufficient to render the tape playable or if additional steps such as cleaning are required. This approach provides a key complementary, measurement-based method for assessing tape degradation, enabling non-destructive identification of underlying mechanisms prior to intervention. This has already been successfully applied to support the understanding of the workflow developed for the treatment of Pyral tapes[10] and to understand the effects of sub-zero storage on film magnetic soundtracks[30]. This study also supports the current shift towards more systematic investigations of issues facing audiovisual heritage materials using state-of-the-art analytical techniques[31–33]. As tape players and heads become increasingly rare and tapes continue to decay and become more fragile, this approach allows for targeted treatment, helping to reduce damage caused to tapes and players.

Further, based on our analysis, we propose a modified framework for describing the condition of tapes for which binder hydrolysis is the main chemical degradation mechanism. The term soft binder syndrome is "applied to all tapes that show stickiness, shedding, and/or squealing, whether they respond to baking or not"[6]. Within this umbrella category, however, the further nomenclature is unclear: SSS acts as a defined sub-category, but the position of many other tape syndromes within this framework remains unspecified. We therefore propose that SBS should be subdivided based on the underlying degradation mechanism, rather than merely according to playback behaviour. One sub-category comprises *hydrolysis-driven SBS*, which is the focus of this work. In this category, the short-chain ester byproducts of PE-PU binder hydrolysis are detectable and are a major contributing factor to the tape condition. It covers tapes with conventional SSS that respond to baking, such as the ¼″ Ampex 406 and 2″ Ampex 456 tapes, as well as the Pyral CJ87 that requires an additional cleaning step to become playable. In this framework, the different symptoms are understood as observable manifestations of hydrolysis-driven degradation rather than due to distinct mechanisms. Our observations suggest that differences in macroscopic degradation behaviour for tapes showing binder hydrolysis reflect variations in tape formulation, layer adhesion, and inhomogeneous degradation rather than fundamentally different chemical degradation pathways. A second sub-category comprises *non-hydrolytic SBS*, with tapes that exhibit binder-related playback issues but without detectable PE-PU hydrolysis or associated byproducts and that do not chemically respond to baking. For example, SONY PR-150 tapes squeal during playback, but do not show IR signatures of SSS that do not change upon heating (see Suppl. Fig. 6). The behaviour in that case is rather consistent with a plasticized, low-Tg (glass transition temperature) binder state[5]. Furthermore, adhesion syndrome observed in some tapes also falls into this category. The magnetic layer adheres to the back of the adjacent tape layer, but there are no signatures of hydrolysis, and these tapes do not respond to heat treatment, requiring specialised cleaning procedures to make them playable[11,12]. Our proposal for this classification scheme is outlined in Fig. 7.

Taken together, these findings support a reinterpretation of tape degradation classifications in terms of underlying chemical and microscopic origins, rather than macroscopic behaviour alone. While this study has shown conclusively that binder hydrolysis is a common chemical mechanism across several different types of tape failures (stickiness, adhesion and delamination), further work is needed to exhaustively map remediation strategies to laboratory analysis results. While spectroscopic techniques can identify chemical changes at the binder surface, complementary microscopic observations are necessary to understand how these changes affect the physical behaviour of tapes during handling and playback. Equally importantly, it is possible to make these determinations on small pieces of tape. Other techniques, such as vibrating sample magnetometry and X-ray fluorescence, can additionally be used for simultaneously probing further aspects within our proposed multimodal scheme[30,33–35]. Overall, multimodal diagnostic approaches move tape preservation beyond trial and error, enabling objective classification and better targeted remediation of degraded audiovisual heritage.

Data Availability

The raw ATR-FTIR spectra and in-house Python scripts for processing have been placed in a publicly-accessible repository and will be made available upon article publication. DOI: 10.5281/zenodo.21478967.

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Competing interests

The authors declare no competing interests.

Additional information

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