Available online at www.sciencedirect.com

SCIENCE @ DIRECT®

Analytica Chimica Acta 559 (2006) 257–263

ANALYTICA CHIMICA ACTA

www.elsevier.com/locate/aca

Development of a fast and non-destructive procedure for characterizing and distinguishing original and fake euro notes

A. Vila [a], N. Ferrer [b], J. Mantecón [c], D. Bretón [c], J.F. García [a,*]

[a] Departament de Pintura, Conservació-restauració. Facultat de Belles Arts, Universitat de Barcelona, Spain
[b] Unitat d'espectroscòpia molecular, Serveis Científico-Tècnics. Universitat de Barcelona, Spain
[c] Cuerpo Nacional de Policía, Policía Científica, España, Spain

Received 26 April 2005; received in revised form 18 November 2005; accepted 23 November 2005
Available online 18 January 2006

Abstract

Since the introduction of the euro as the common currency in most of the countries of the European Union, the production of counterfeit banknotes has increased steadily. The European Central Bank has distributed information on a systematic procedure to distinguish genuine notes from counterfeits based on the look, feel and tilt of the notes. Counterfeits, however, have remained difficult to detect. In order to improve such detection, a procedure based on the analysis of several areas of euro notes using microscope ATR-infrared spectroscopy is proposed. This procedure is fast, robust and non-destructive and it can be applied in situ. The present study is focused on the denomination most frequently falsified, the 50€ note, but 100€ notes were also analysed. The inter- and intra-bank reproducibility of the original notes was also evaluated. Results indicate that characteristics of the spectra depend mainly on the area of the note studied and, furthermore, these characteristics do not change with the nominal value of the notes. Counterfeit banknotes were also analysed and were clearly distinguished from authentic notes in all cases. Unlike genuine notes, the spectra of fakes are the same in all areas of the note analysed.

Keywords: Notebanks; Counterfeits; Artistic prints, Artworks; Original versus fakes discrimination; ATR infrared spectroscopy

1. Introduction

On January 1, 2002, the euro was introduced as the common currency in the greater part of the countries belonging to the European Union. Banknotes are produced by 12 financial institutions, the 10 central banks of Austria (N), Belgium (Z), Finland (L), France (U), Greece (Y), Italy (S), the Netherlands (P), Portugal (M), Spain (V) and Sweden (K), together with two other printing factories located in Germany (X). The origin of each banknote is clearly indicated by the first letter of the serial number on the note.

Banknotes include several security features that can be easily checked simply by following the procedures disseminated by the European Central Bank (ECB) in the document titled "Look, Feel and Tilt" [1]. The different tests are based on the observation of the note with the naked eye in reflected and transmitted light and on the perception, by touch, of the surface. Banknotes also include other basic security features based on the response of different parts of the front and reverse sides to light from the infrared and ultraviolet spectra. Some of these characteristics are routinely used in shops to establish the authenticity of euro notes.

In spite of all these security characteristics, however, as soon as the euro appeared, counterfeit notes also began to emerge. According to the ECB, in the first semester of 2002 the number of counterfeit euro notes was only 7% of the number of counterfeit notes in the currencies that the euro replaced. This value increased six times during the second semester of that year and today is up to 91% [2]. Quality has gone up with quantity during this time, paralleling new computer techniques and printing process development. The latest fakes can easily pass a routine examination of the visible features pointed out by the ECB. The quality of such fakes can be attested to the daily experience of many people. The 50€ note is the denomination most frequently counterfeited [2].

To fight against the circulation of counterfeit notes, some devices based on non-spectroscopic measurements have been

* Corresponding author. Tel.: +34 934021281; fax: +34 934021233.
E-mail addresses: avila@sct.ub.es (A. Vila), nferrer@sct.ub.es (N. Ferrer), jfgarcia@ub.edu (J.F. García).

0003-2670/$ – see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.aca.2005.11.084

produced and adopted by many shops. These devices measure the intensity of the signal when some areas of the banknote are irradiated with infrared or ultraviolet light [2]. They also check the distribution of magnetic ink on the surface.

The objective of this study is to establish a fast and non-destructive procedure to characterize and discriminate between genuine and fake euro notes, based on the spectroscopic characteristics of the materials included in their composition. This spectroscopic approach is a powerful tool to identify counterfeit notes because it yields a huge amount of information that can only be reproduced if the same materials and structure are present in the non-original documents. This primary objective does not require identification of the composition of the components of the banknotes but, instead, only requires information on the original spectra and their variability, and comparison with the spectra from the suspicious document. This comparison would also allow the grouping of fakes according to the similarities of their spectra and could therefore help to identify their origin and the falsification procedures.

The procedure proposed is based on the acquisition of the middle Infrared spectrum of several areas of the banknotes by using the microscope in attenuate total reflection mode (ATR). A similar procedure was applied in the study of artistic prints. This technique allows the fast registration of spectra and the possibility of in situ examination using portable equipment.

2. Experimental

2.1. Reagents

- Original 50€ banknotes from three different countries and 100€ banknotes from one country:
  - Spain (V)
    - 50€ (V05258174719 (V052), V00755353291 (V007), V13344854224 (V133)).
  - Germany (X)
    - 50€ (X09512985773 (X095), X02388719486 (X023), X00446761352 (X004)),
    - 100€ (X04529894096 (X045)).
  - France (U)
    - 50€ (U16163971691 (U161), U14258009237 (U142), U04076071151 (U040)).
  - Italy (S)
    - 50€ (S1020600953, S0943668889, S1196679416).
  - Counterfeit banknotes of 50€ and 100€ provided by the Spanish Police (different provenances).
    - 50€ (V03223414784 (V032), V04522309193 (V045), V25819037125 (V258)),
    - 100€ (V50241071218 (V502), S05118492715 (S051)).

3. Apparatus

3.1. Fourier transform infrared spectroscopy

The analyses were done with a BOMEM MB-120 Fourier Transform Infrared Spectrometer, equipped with a Spectra-Tech Analytical Plan microscope with an attenuated total reflectance (ATR) objective. The spectrometer has a KBr beamsplitter and a Globar source. The microscope has its own MCT detector, refrigerated with liquid nitrogen. The area analysed is about 200 μm^2 and sample preparation is not necessary.

Spectra were recorded between 4000 and 720 cm^{-1} with a resolution of 8 cm^{-1} and an accumulation of 200 scans.

3.2. Procedure

Four different areas on the 50 and 100€ notes were selected for study. The areas of the notes analysed are:

On the front:

- The blue colour of the European flag; at the top left of the banknote.
- The European Central Bank red letters (green letters in 100€ notes); next to the European flag.
- The shiny hologram; at the bottom right of the banknote.

On the reverse:

- A white area; on the right side of the banknote.

The analyses of the surface were done by pressing the zinc selenide crystal to the area selected, with the microscope operating at the visible wavelength. The importance of this technique is that it is non-destructive. It works through contact of the crystal with the area of interest. Because is a microtechnique, three measurements of each area and note were examined.

4. Data treatment

All the results were processed with GRAMS 32 (Galactic) Software. The spectra were treated with a baseline correction, CO_2 zap and a Y-offset.

Principal component analysis [3] was performed by using Matlab Software. All spectra were scaled according to the mean and the standard deviation obtained from the original set of banknotes.

5. Results and discussion

The proposed procedure is based on the acquisition of middle infrared spectrum from different areas of the banknote due to the capability of its fingerprint region to yield useful information for qualitative analysis. Attenuated total reflection technique with Microscope (μ-ATR) is a fast and non-destructive technique that allows the selection of well-defined small areas of a document.

The main problem found in the application of this procedure is that the pressure required to obtain the spectrum was slightly greater than usual. This pressure does not produce any observable banknote deterioration. It is probably necessary because the penetration of inks in the cotton network makes the contact between the material and the ATR crystal difficult.

The present study focused on the most frequently counterfeited denomination, the 50€ note, but the procedure can also be applied to any other denomination, as can be deduced from the results obtained for the 100€ notes.

Four different areas were selected for the study. Several areas were analysed in order to provide a large data set that would increase the probability of detecting the different materials included in the banknote and, therefore, improve the possibility of discriminating between originals and fakes. The number of areas studied can be increased if the complexity of the counterfeit banknotes means that more information is required.

First, inter- and intra-bank reproducibility were evaluated by analysing some documents printed by the German (X), French (U) and Spanish (V) banks. Then, results were compared with those from fake notes. As results obtained in the study of Italian (S) original notes are exactly the same than those obtained for the other central banks, the discussion about reproducibility is restricted to the German, French and Spanish notes.

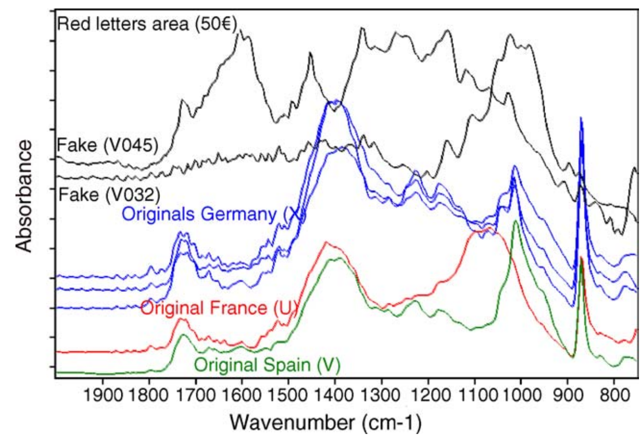

Fig. 2. Infrared spectra (2000–750 cm^{-1}) of the red letters area from genuine and fake 50€ notes. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

5.1. Original intra- and inter-bank production reproducibility

5.1.1. Fifty euro banknotes

Mid-infrared spectra of the *European flag* blue area from three German banknotes are shown in Fig. 1. The spectra of the German notes are quite reproducible, and spectroscopic peaks in the range 1160–998 and at 898 cm^{-1} correspond to the cellulose in the supporting paper. Other peaks, at 1776, 1750–1700, 1604, 1241, 980, 913, 815 and 778 cm^{-1}, must be associated with the mixture of compounds used in this part of the note.

In the same figure, spectra collected on the corresponding location on French and Spanish notes are also reported. Their reproducibility, like that of the German notes, is quite high. However, there are slight differences. These singular aspects are, for German banknotes, the peaks at 1776 and 1244 cm^{-1}, which appear as just a shoulder in the U and V notes; for French notes, the intensity of the peak at 1724 cm^{-1}, higher than the corresponding bands in the X and V banknotes; and, finally, for Spanish notes, the low intensity of the aforementioned peaks.

The next area studied was that corresponding to the *red letters* (the initials of the European Central Bank in several languages) located to the right of the European flag. One interesting characteristic of these letters is that they are embossed. The analysis is centred on the ECB set. The spectra of three banknotes from Germany were very similar, which indicates that the material composition of the letters in the different notes is reproducible (Fig. 2). The profiles of these spectra include two peaks, located at 1410 and 870 cm^{-1}, which, together with the bands at 2518 and 1795 cm^{-1} (Fig. 3), could be attributed to the inclusion of calcium carbonate as a main component in the mixture. This compound could be responsible for the relief of the letters. It is interesting to note that the spectra do not show any signal that could be related to the presence of cellulose in the area analysed. Other peaks of the spectrum of ECB letters, 1776 and 1750–1700 cm^{-1} were also found in the zone of the blue flag and may correspond to common compounds included in the printing material of both areas. Finally, five bands, 1225, 1174 1041, 1015 and 950 cm^{-1}, remain unassigned and could be associated with the ECB area. In addition, bands between 3000–2800 cm^{-1} (Fig. 3) show strong absorption and belong to CH_2–CH_3 stretching vibrations.

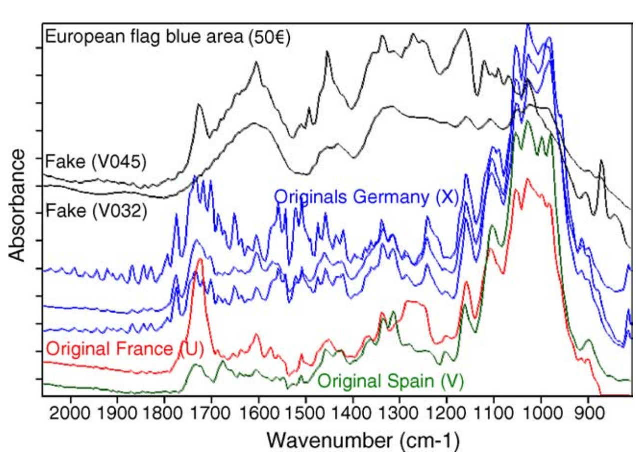

Fig. 1. Infrared spectra of the European flag blue area from genuine and fake 50€ notes. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

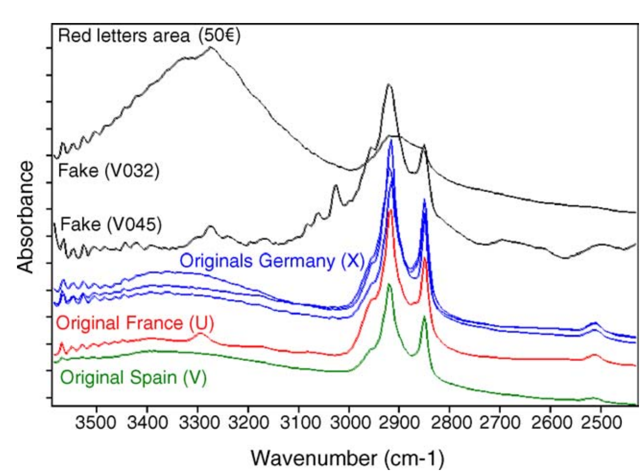

Fig. 3. Infrared spectra (3600–2400 cm^{-1}) of the red letters area from genuine and fake 50€ notes. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

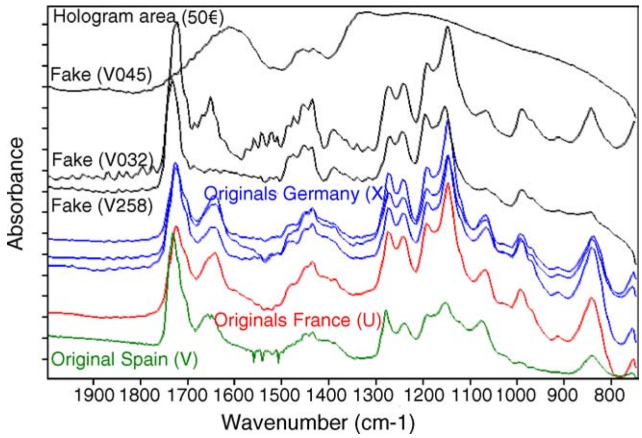

Fig. 4. Infrared spectra of the hologram area from genuine and fake 50€ notes.

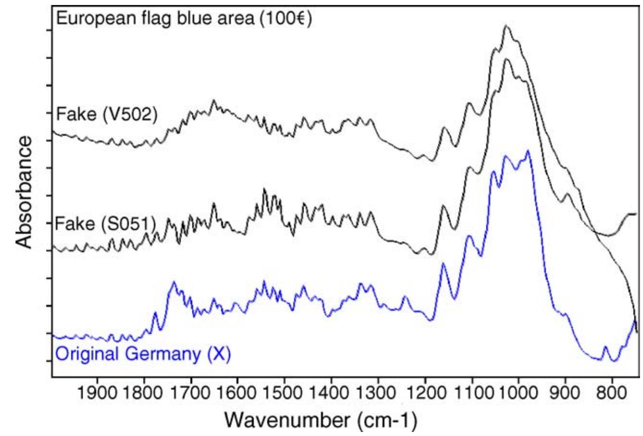

Fig. 6. Infrared spectra of the European flag blue area from genuine and fake 100€ notes. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

In addition, spectra obtained for banknotes printed at the German (X), French (U) and Spanish (V) central banks appear, in general, to be quite similar (Fig. 2). Nevertheless, the French notes differ from the German and Spanish ones, due to the presence of absorption bands at 3300 and 1100–1050 cm^{-1}.

The third area of the front studied was the *hologram*, which is covered by a plastic film. According to the ATR technique characteristics, the spectrum would correspond to this film. Fig. 4 shows the results of the analysis of the three banknotes from Germany. The three spectra are equivalent. The hologram spectra include peaks at 1725, 1645, 1434, 1271, 1242, 1186, 1146, 1067, 991, 838 and 757 cm^{-1}. These absorption bands identify the plastic film as an acrylic polymer.

Fig. 4 also reports the spectra corresponding to the hologram area of banknotes from France and Spain. Again, the reproducibility of the spectra from genuine banknotes is complete.

It should be stressed, however, that the discriminative capability of the ATR technique in this area is less sensitive than that obtained in the flag or letter zones.

The *white area* located on the right side on the reverse of the note was also studied. The spectra for the three banknotes printed in Germany are shown in Fig. 5. The high reproducibility of the spectra of three notes is clear. Most peaks correspond to the cellulose whereas the other small peaks found were also registered in the blue area of the reverse (1776, 1750–1700, 815 cm^{-1}). The most important peak is located at 980 cm^{-1}. Therefore, it is not possible to associate any specific band with this part of the note. Spectral reproducibility between Germany, Spain and France is very high (Fig. 5).

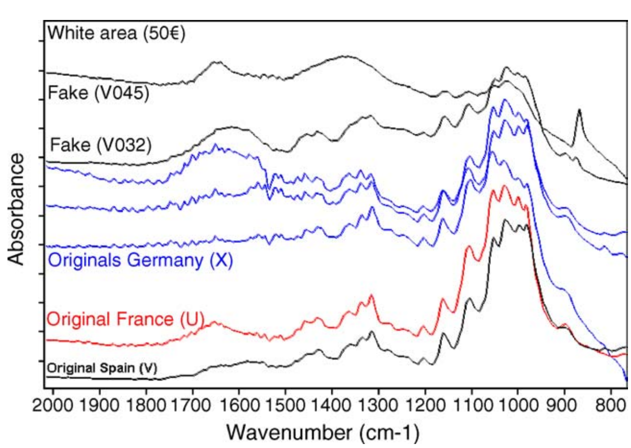

Fig. 5. Infrared spectra of the white area from genuine and fake 50€ notes.

Overall, the analysis of these four areas of 50€ notes by ATR infrared spectroscopy indicates the good intra- and inter-reproducibility of the spectral behaviour of banknotes printed by different central banks, and the presence of several characteristic peaks in the spectra, which are potentially useful for detecting counterfeit notes.

5.1.2. Hundred euro banknotes

In order to explore the application of the proposed approach to banknotes of other denominations, spectra from the same areas of a 100€ note from Germany were also obtained.

Fig. 6 presents the spectra obtained from the blue area of the *European flag* of the original banknote. Authentic 100 and 50€ banknotes show highly similar spectra. In this case, an important contribution to the total spectrum is due to cellulose of the substrate of the note. The other bands, 1773, 1750–1700, 1600, 1475, 1244 and 975 cm^{-1}, can be related to the other materials used in the note's production. It is remarkable that the band at 1773 cm^{-1}, established as a characteristic of the notes printed by the German bank, also appears in this 100€ note. As the same information is obtained both in this case and in the 50€ study, it could be expected that the ATR-IR approach could identify counterfeit notes regardless of their denomination.

The analysis of the initials of the European central bank, in this case *green letters* instead of red, provides similar information to that obtained from the 50€ notes. Fig. 7 shows the spectra of the original and the two fakes. The most important signals at the spectrum from the authentic note correspond to the carbonate peaks. As in the case of the 50€ spectrum, it is hard to distinguish any peaks from cellulose due to the thickness of the letters. There are also some peaks found previously in the flag area, 1750–1700 1240 and 980 cm^{-1}, including a very small band at 1778 cm^{-1}. The rest of the peaks, 1226, 1175, 1123,

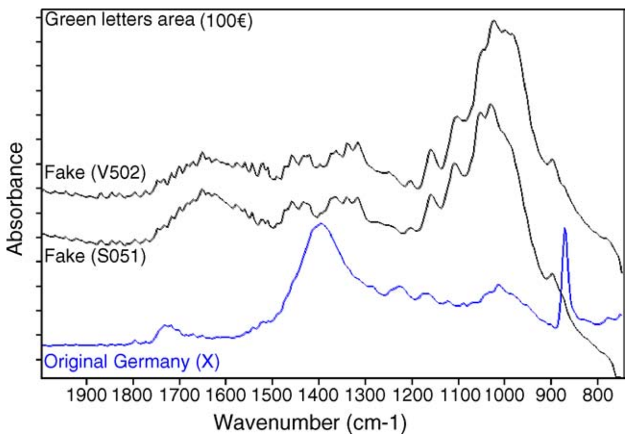

Fig. 7. Infrared spectra of the green letters area from genuine and fake 100€ notes. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

1066–1012 cm^{-1}, even the smaller, 1675–1650 cm^{-1}, show the same shape found in this area of the 50€ notes. No signal can be associated with the new colour. The dependence of the spectra on the area of the note studied is clear, however, regardless of the note's denomination.

The third area analysed is the *hologram*. The spectra obtained for the original and the two fakes are shown in Fig. 8. The spectrum of the original note is the same as that obtained for the 50€ notes.

The last zone studied is the *white area* of the reverse side. Discussion in this case is also limited because the spectrum obtained for the original (Fig. 9) is again the same as that acquired for the 50€ notes. The main component detected is cellulose together with a few peaks already observed on the spectrum of the flag area, 980 and 815 cm^{-1}.

The study of this 100€ note confirms the results obtained from the 50€ banknotes. It also shows the potential of the proposed procedure for providing information that can be used for characterization and discrimination purposes. Furthermore the spectra of the different areas do not depend on the nominal value of the note but they do maintain some characteristics associated with their geographic origin.

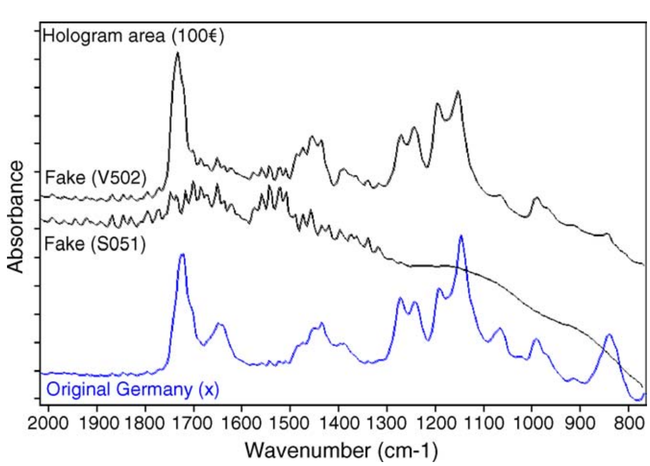

Fig. 8. Infrared spectra of the hologram area from genuine and fake 100€ notes.

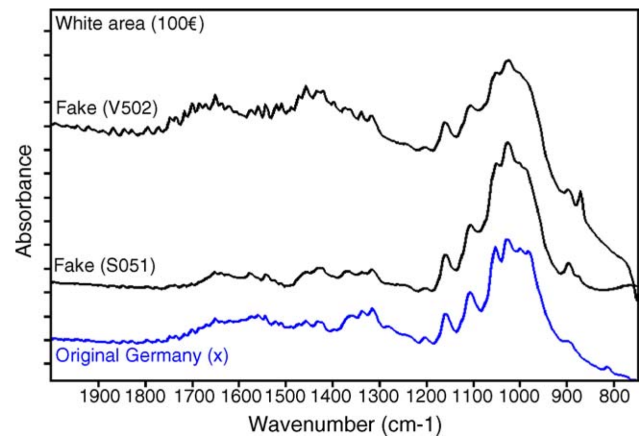

Fig. 9. Infrared spectra of the white area from genuine and fake 100€ notes.

5.2. Original banknotes versus fake banknotes

5.2.1. Fifty euro banknotes

Several counterfeit banknotes were analysed in order to compare the spectra obtained with those corresponding to the genuine notes.

Fig. 1 shows the spectra of the blue *European flag* area of two counterfeit banknotes together with the original spectra of this zone. The main differences between the fake V045 and the original are the presence of peaks at 3100–3000 cm^{-1} (typical of double bonds), the absence of cellulose, and the characteristic bands located at 1776, 1244, 980 and 815 cm^{-1}. On the other hand, the spectrum of fake V032 shows an important contribution of cellulose; but it can also be distinguished from an original by the presence of a signal at 873 cm^{-1}, which does not correspond to the carbonate, and by the absence of 1775, 1750–1700, 1244 and 980 cm^{-1} bands.

The next area studied was that corresponding to the *red letters*. The spectra obtained for the two counterfeit notes are shown in Fig. 2. The main difference between originals and counterfeits is the absence of calcium carbonate. For V032, its being counterfeit is corroborated by the absence of bands at 1750–1700 and 1227 cm^{-1} and by the important contribution of cellulose to the spectrum. In fact, the spectrum of this part of the banknote is practically equal to that already shown (Fig. 1) which corresponds to the European flag area. This occurs frequently with counterfeit notes: regardless of where the spectrum is registered, the profile obtained is the same. Equivalent results are obtained in the study of this area for the V045 counterfeit banknote.

Principal component analysis was performed on the spectra obtained from this part of the banknotes. The results obtained clearly confirm the capability of the proposed procedure to discriminate original from counterfeit banknotes. The plot of the score values corresponding to principal component (PC) 1 versus principal component (PC) 2 of each spectrum (Fig. 10) shows two well-differentiated sets, one including fakes and the other originals. PC1 can be related to the contribution of cellulose and carbonate to the spectra, whereas PC2 denotes the contribution of carbonate. The two groups are differentiated according to the values of the PC2 score. It is interesting to point out that any

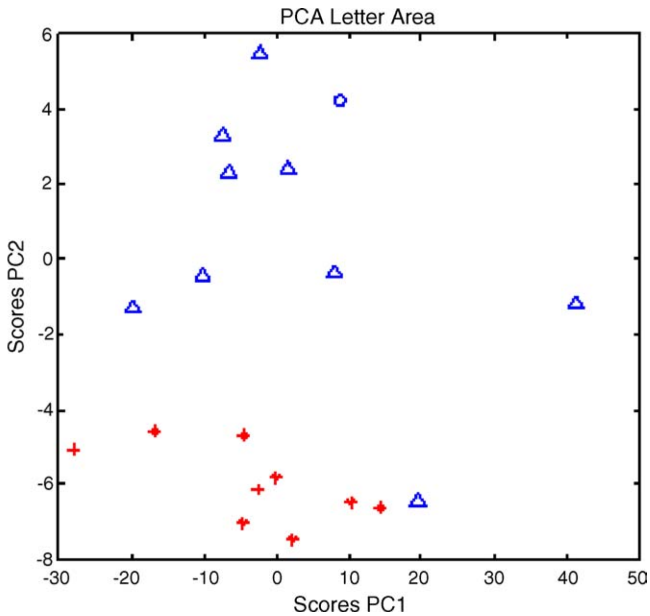

Fig. 10. Plot of the score values corresponding to principal component 1 vs. principal component 2 of each spectrum of the letter area of genuine [50€ (△) and 100€ (◯)] and fake [50€ (*) and 100€(+)] notes.

spectrum of low intensity can lead to the misclassification of the banknote. This is the case of the original Spanish banknote V00755353291, which appears among the counterfeit group. The low intensity of this spectrum may be attributable to poor contact between the ATR crystal and the banknote materials during the signal acquisition process.

Spectra from the *hologram* area of the original banknotes were completely reproducible for any element or bank because they all came from the same polymer film. The simplicity of this composition is a problem for identifying counterfeit notes (Fig. 4). The problem arises because, in some counterfeit notes, the original polymer, V032, or a very close compound, V258, was used. In V258 the only difference is the absorption band at $1643\,cm^{-1}$. When the genuine polymer is not used, the spectrum is completely different from the original, V045. In this sense, the information obtained from the analysis of this area allows disqualification of a fake banknote but does not guarantee confirmation of an original.

The last comparison was performed on the *white area* of the reverse. Fig. 5 includes the spectra corresponding to two counterfeit notes and several originals. The spectra corresponding to the originals mainly show the presence of cellulose, which is also the case for the two fakes. As cellulose is the base of any paper, the analysis of this part can contribute only to a limited extent to distinguishing between genuine and counterfeit notes. This general conclusion has exceptions: whenever the counterfeit notes include some additional compounds, as happens in note V045 where carbonate peaks appear, 1400 and $875\,cm^{-1}$, disqualification is possible. The value of this area would be equivalent to that discussed for the hologram area of the note.

The results obtained using the proposed ATR-infrared spectroscopy procedure on the different areas allowed us to distinguish all of the counterfeit notes studied from the authentic banknotes. The contribution of the analysis of each of the four areas is not equal, but it does provide complementary information that could hardly be matched by a banknote produced using any illegal procedure.

5.2.2. Hundred euro banknotes

First comparison between original and fake spectra was done on the *European flag* area (Fig. 6). Fake spectra show the presence of cellulose in both cases, but the contribution of the other materials detected in the original do not appear in the fake notes. This result can easily be used to distinguish between the original banknote and the fakes studied.

The next area studied was that corresponding to the *green letters*. The spectra obtained for fakes (Fig. 7) are very similar to those registered in the European flag area. The main bands correspond to the presence of cellulose and there are no signals that could be related to carbonate, the principal component in the spectrum of the genuine banknote. The other characteristic peaks of the original banknotes do not appear either. It is important to stress that the spectra of the fakes do not depend on the area studied and that the results obtained are equivalent to those from the comparison of 50€ notes as it can be observed in the results of the principal component analysis (Fig. 10).

The same results were also obtained in the study of the *hologram* area. In this part, the spectra of fakes are again equivalent to (V502) or totally different from (S051) the spectrum obtained from the original note (Fig. 8).

Finally, the comparison of results obtained in the analysis of the *white area* of the authentic and the fake banknotes also gives the same results as in Section 5.1.1. In this area, the spectra of the authentic and the spectra of the fakes can be explained mainly by the presence of cellulose in the substrate. The possibility of distinguishing counterfeit from genuine notes depends on the detection of any other compound, as happens in the V502 fake, where 1400 and $875\,cm^{-1}$ peaks can be associated with the inclusion of carbonate in the material of that zone. A similar situation was found with a 50€ note (Fig. 9).

The results obtained in our examination of genuine and counterfeit 100€ notes suggest that our procedure could be applicable to the detection of fakes of any denomination. In addition, the coincidence of results yielded by the studies of 50 and 100€ notes supports the robustness of this approach.

6. Conclusions

The proposed procedure, based on the analysis of several areas of the banknotes using the ATR-FTIR Microscope techniques, allows us to distinguish between genuine and fake euro notes. The chemical information obtained from each area is complementary for this discrimination purpose and it can be extended, by increasing the number of zones analysed, whenever it was necessary to distinguish any particular falsification case.

The procedure is fast, non-destructive, robust and can be applied in situ.

The results indicate that original banknotes have a reproducible spectrum for each area which does not depend on the value of the note and which varies slightly with the origin of the note. On the other hand, the spectra of fake notes are usually the same for any area analysed (except the hologram), and they are clearly different from those found in authentic notes.

Acknowledgements

We wish to thank the Ministerio de Ciencia y Tecnologia, project BHA-2002-02-02756. We also thank Silvia Lacorte for her suggestion that we apply our research to the study of euro banknotes, and Angels Miquel for her comments.

References

[1] “Recognizing the Euro”, The European Central Bank Press Event, Publication Statistics: Banknotes & coins, Monetary Policy Payments & Securities.

[2] “Distingir el gato de la liebre” (Seeing through counterfeit tricks), Financial pages of La Vanguardia newspaper, Sunday 24th October 2004.

[3] K.H. Esbensen “Multivariate data analysis—in practice, An introduction to Multivariate data analysis and experimental design, Ed. CAMO ASA (2000).