Research on the Application Technology of Color Digitization for Leather Coatings

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Research on the Application Technology

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Abstract

This study aims to explore the innovative application and practical Value of digital color technology in color management and intelligent color matching across the leather supply chain. Firstly, through the implementation of digital spectral monitoring of pigments and throughout the pigment production process, color data stability is ensured at the source. Secondly, the integrated application of digital color technology with automated weighing systems enables the full automation of the entire workflow from color data to pigment formulation for leather coatings. Furthermore, by leveraging intelligent optimization algorithms, the system performs dynamic correction of formulations when color difference exceeds tolerance thresholds. This significantly enhances color matching efficiency, provides optimal solutions for managing metamerism, and offers cost-effective alternative formulas. The establishment of a centralized color database and digital color standards spanning the supply chain facilitates “end-to-end” color management and quality traceability from raw materials to finished products. Empirical results indicate that this technology establishes an innovative paradigm for color management characterized by high efficiency, stability, and traceability, providing essential support for global collaborative production and digital transformation of the leather industry.

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Keywords: Digital Color Technology, Color Stability, Color Matching Efficiency, Color Management, Quality Traceability, Metamerism

1. Introduction

Against the backdrop of increasingly fierce competition in the global leather products market, color management has become a key factor determining product added value and market competitiveness. Traditional leather color management primarily relies on manual visual comparison and empirical judgment, faces challenges such as low color matching efficiency, difficult color difference control, and challenges in tracing color-related problems, making it difficult to meet the demands of modern leather industry for refined and intelligent production. With the rapid development of information technology, color digitalization technology offers a novel solution for color management in the leather supply chain. This study focuses on the innovative application of color digitalization technology in color management and intelligent color matching within the leather supply chain. By systematically analyzing key technologies such as pigment color monitoring, automated color matching, and intelligent optimization algorithms, a central color database and digital standards spanning the supply chain are constructed. Furthermore, it explores the feasibility of full-process color management and quality traceability from raw materials to finished products, providing theoretical support and practical guidance for the digital transformation of the leather industry.

Instruments Model Company

Laser diffraction particle size analyzer HELOS-CUVETTE SYMPATEC GmbH

Spectrophotometer Datacolor 200M DATACOLOR

Electronic balance AL204 METTLER TOLEDO

2. Experimental Instruments

The experimental instruments involved in the data for this paper are as follows:

3. Overview of Color Digitalization Technology

The development of color science can be broadly categorized into three stages: scientific definition of color - development of color measurement methods - development of automated color formulation [1, 2]. Between 1920 and 1930, Wright and Guild conducted a series of color matching experiments. Later, the International Commission on Illumination (CIE) formally introduced the CIE 1931 standard colorimetric system based on these experiments, defining the standard observer, chromaticity coordinates, and standard illuminants[3]. Subsequently, in 1964 and 1976, the standard observer was supplemΔented to expand the field of view, and uniform color spaces were defined.

*

ΔEab

The CIELAB color differenc between different colors was defined as the Euclidean distance between them[4]. Later, weighting functions were introduced to correct the perceptual inconsistencies in the blue and neutral gray regions[5], making the calculated color difference value ΔE00 highly correlated with human visual observation.

* * * *

In the equations, ΔEab

is the CIELAB color difference, ΔL and ΔL' are the lightness difference, Δa and Δb are the chroma differences. ΔE00 is the CIE2000 color difference, ΔC' and ΔH' represent the chroma difference and hue angle difference, respectively. kL, kC and kH are parametric factors, SL, SC and SH are weighting functions, and RT is the rotation function.

Furthermore, to eliminate dependence on human vision for color measurement, developers began designing electronic instruments. After the 1960s, photoelectric colorimeters and spectrophotometers based on photoelectric detection technology became mainstream [6], eliminating subjective errors and truly achieving objective, repeatable spectral measurement. Entering the 21st century, modern instruments such as multi-point spectral enhanced imaging colorimeters have been developed, capable of rapidly acquiring complete color distribution on sample surfaces, expanding measurement from "point" to "area," with significantly improved accuracy and efficiency. The color difference recognition accuracy of current color measuring instruments far exceeds that of the human eye. After the establishment of comprehensive color science theory and color measurement methods, the development of formulations for target colors became feasible.

With the rapid development of the Internet, color development has entered a new stage: data network construction and end-to-end color management. The connection between OEMs, tanneries, and various raw material suppliers has become increasingly close. The way OEMs transmit color development requirements has gradually shifted from physical target color standards to digital target colors, forming a complete data chain. The advantages this brings are unparalleled. Through data sharing between OEMs and suppliers, faster feedback on issues and color requirements, more convenient quality problem traceability, and more precise production control can be achieved [8].

4. Application of Color Digitalization Technology in the Leather Industry

4.1 Transmission and Control of Color Difference in the Leather Supply Chain

The color difference (ΔE) between the finished leather and the target color accumulates throughout the manufacturing chain. Initially, during pigment production, color is mainly influenced by the amounts of intermediates and monomers added and the preparation process, leading to certain color differences (ΔE1) between pigment batches [9]. At the pigment paste manufacturer, pigments need to be ground and blended to produce pigment paste. Differences in pigment particle size and content of the pigment paste will lead to color difference (ΔE2). Meanwhile, product stability issues such as pigment sedimentation and agglomeration of the pigment paste supplier can also cause color differences (ΔE3) [10]. Color differences at the coating production end mainly stem from the color difference between the color design and the target color (ΔE4) and the color difference during production and compounding (ΔE5). Similarly, compatibility issues during the use of the the finished coatings may also cause color shifts (ΔE6) [10]. Finally, when the finished coatings are applied at tanneries, differences in the tanneries' finishing methods and coating film thicknesses will cause the finished leather products to deviate from the designed color, accumulating another layer of color difference compatibility issues(ΔE7) [11]. Assuming the color difference distribution follows a normal distribution, without establishing control over the production and application processes, the color difference will accumu-

Figure 1: Production process and quality control process of pigment paste, as shown in Figure 1

late layer by layer:

ΔE = ΔE1 + ΔE2 + ΔE3 + ΔE4 + ΔE5 + ΔE6 + ΔE7

Conversely, under the ideal state of production process control, the color difference between the finished product color and the target color (ΔEideal) should be controlled to the sum of the color design difference (ΔE4) and the preset spraying color difference at the tannery (ΔE7).

ΔEideal = ΔE4 + ΔE7

The purpose of the color digitalization system is to reduce color difference problems caused by various production stages (ΔE2, ΔE5) and color development (ΔE4), thereby

improving the batch-to-batch color stability of leathers and reducing the difference between the finished product color and the target color.

4.2 Color Control in Pigment Paste Production Process and Batch Stability

Pigment paste batch stability is the most critical factor affecting the color stability of finished products at tanneries or OEMs. If the color difference between pigment paste batches is too large, it can reduce color matching efficiency, and at worst make it impossible to achieve the target color. Therefore, pigment paste suppliers should establish reasonable control and error correction mechanisms for their production processes to reduce inter-batch color difference ΔE2. The color data system plays an indispensable role in product quality control.

Results Particle Size / μm L/ΔL a/Δa b/Δb ΔE (< 0.50)

In the pigment paste production and quality control processes, “paste milling” and “finished product inspection” are two key nodes shared by both processes. The most crucial testing item in finished product inspection is hue testing, which is precisely the responsibility of the color data system. In general pigment paste production,

Table 1 : Particle size and hue of DP-5223

Batch In Process Control

Standard Qualified 0.593 81.48 20.14 52.64 /

A Qualified 0.587 0.05 0.12 0.19 0.23

B Qualified 0.597 0.07 0.09 -0.11 0.16

C Unqualified 0.614 -0.01 -0.05 -0.68 0.68

D Unqualified 0.580 -0.11 0.06 0.89 0.90

E (Mix C with D) Qualified 0.599 -0.09 0.18 0.23 0.31

Table 2 : Maximum color difference data for each production batch of DP-5223

|ΔLmax| |Δamax| |Δbmax|

Production Process

0.87 0.65 1.63

Original Process

0.49 0.26 0.62

After Setting Correcting Process

Figure 2: Historical records of color deviation for each batch of DP-5223

the color data system serves the function of associating historical batches with color data. Furthermore, the color data system can detect and record color changes during the production process, which is crucial for batch management and problem traceability.

Δemax

1.14

0.72

The hue of pigment paste is significantly influenced by particle size and solid content. A relatively simple and feasible management method is to re-mix batches with opposite hue trends, which can offset the hue deviation and thus control the batch color difference within an acceptable range. As shown in Table 1, taking DOWESION® GOLDEN YELLOW DP-5223 as an example, its pigment is typical P.Y.110, the color difference values (ΔE) of

batches C and D deviated from the standard sample, measuring 0.68 and 0.90 respectively, due to insufficiently strict particle size control. Both values exceeded the specified control threshold of $\Delta E < 0.5$. In contrast, the color difference was successfully lowered to 0.31 by means of batch mixing, fulfilling the specified requirements.

An analysis of color differences between historical batch samples and standard samples for various pigment pastes was conducted (see Table 2 and Figure 2). Under the original process conditions, the maximum inter-batch color difference ($\Delta Emax$) reached 1.14. After establishing a pigment particle size-color correlation data system and implementing corrective processes, $\Delta Emax$ was reduced to 0.72. Moreover, fluctuations in Lab values were significantly minimized. As shown in Figure 3, the production process management level has been improved from 3 level (USL=1.0) to 5 level (USL=0.6). The corrective process is necessarily initiated only after production has deviated from normal conditions and irreversible results have occurred. Typically, after nonconforming products are produced, correction must wait until the next production batch. Therefore, this approach

σ σ

Table 3: Color matching formulation using series pastes

Pigment Pastes Color Matching

Optimized Formulation DOWESION CAMEL H253 45.52 0.00

DOWESION CAMEL H256 0.00 20.27

DOWESION RED H351 29.86 29.66

DOWESION VIOLED RED H451 0.00 0.33

DOWESION ORANGE H551 0.00 10.08

DOWESION COFFEE H652 7.58 9.89

DOWESION REDDISH BROWN H656 2.7 0.00

DOWESION GOLDEN YELLOW N235 31.04 46.47

Total Weight 116.7 116.7

requires not only the establishment of a color data system but also the development of a product batch color database to trace back to suitable historical batches for mixing.

4.3 Computer Automatic Color Matching Application Based on Digitalization

Metamerism refers to the phenomenon where two objects appear very close in color under one light source but show a significant color difference when switching to a different light source. Essentially, this is caused by inconsistencies in the reflectance spectra of the two objects. Solving metamerism involves mathematical transformation and solving of multiple parameters under multiple light sources, a problem completely unsolvable by human sensory perception and must rely on computer color matching. Currently, general method is simultaneous matching under several typical light sources (e.g., D65/10, A/10, F11/10, TL/84 light sources) while minimizing the color difference.

Under the constraints of a single light source, the computer will provide multiple color matching results. By continuously adding different constrained light sources, color matching solutions with spectra close to the target color can be obtained, as shown in Tables 3-4. Although the initial color difference under a single light source (D65/10) is relatively close to the target color, it is not the optimal matching result. However, after incorporating multiple light sources (D65/10, A/10, F11/ 10), the color matching solution is identified more accurately. The color formulation also becomes closer to the target color formulation.

Formulation

Table 4: Color matching results under multi-light source constraints

Color Illuminant L/DL a/Da b/Db c/Dc h/Dh DE MI

Target Color D65/10 39.49 26.35 21.44 33.97 39.14 / /

Initial Color D65/10 -0.20 -0.07 -0.73 -0.51 -0.52 0.76

Matching A/10 -0.23 0.31 -0.70 -0.27 -0.71 0.80 0.39

Formulation F11/10 -0.14 -0.06 -0.66 -0.50 -0.44 0.68

Optimized D65/10 -0.01 0.01 -0.06 -0.03 -0.05 0.06

Formulation A/10 -0.01 0.05 0.13 0.12 0.06 0.14 0.22

F11/10 -0.01 -0.08 -0.14 -0.15 -0.04 0.16

At present, computer color matching still has pain points. Since the color data in the computer database is input prior to the sale of pigment paste products, the actual produced pigment paste color data will fluctuate according to production batches. This color difference fluctuation is only measurable but unpredictable. Therefore, using pigment pastes from different batches with the same formulation will inevitably result in fluctuations in the final matched color. As shown in the color matching results for three colors in Tables 5-7, after the hue of the color

Table 5: Color matching data for target color A

Sample Light sources L/DL a/Da b/Db ΔE MI

Target Color A CIE LAB 26.11 3.18 -0.94 / /

D65/10 0.39 -0.13 -0.32 0.52

First Color Matching F11/10 0.39 0 -0.35 0.52 0.27

A/10 0.35 -0.34 -0.4 0.64

D65/10 0.01 -0.1 -0.07 0.12

After Correcting F11/10 0.03 -0.01 -0.06 0.07 0.24

A/10 -0.01 -0.31 -0.1 0.32

Table 6: Color matching data for target color B

Sample Light sources L/DL a/Da b/Db ΔE MI

Target Color B D65/10 33.85 6.28 8.95 / /

First Color Matching D65/10 -0.57 -1.06 -1.20 1.69

A/10 -0.75 -1.15 -1.52 2.05 0.61

F2/10 -0.67 -0.79 -1.41 1.75

After Correcting D65/10 0.00 0.00 0.00 0.00

A/10 0.00 0.02 0.01 0.02 0.12

F2/10 -0.01 -0.07 -0.06 0.10

pastes is inputted into the database, the recipes are formulated to match colors A, B, and C, and pastes from other production batches are selected for coatings sample preparation. Colors A, B, and C all exhibited color difference fluctuations during the first color matching attempt relative to the target color. After feeding the matching data back into the color matching software and applying algorithmic corrections, the color difference values under different light sources significantly decreased.

Table 7: Color matching data for target color C

Sample Light sources L/DL a/Da b/Db ΔE MI

Target Color C CIE LAB 46.01 15.31 22.14 / /

D65/10 0.27 -0.34 -0.28 0.51

First Color Matching TL/84 0.32 -0.51 -0.17 0.63 0.29

A/10 0.24 -0.19 -0.41 0.51

D65/10 0 0 0 0

After Correcting TL/84 0 -0.04 -0.02 0.04 0.19

A/10 0.01 -0.18 -0.01 0.18

4.4 Application of Digitalization Technology in Global Color Management

4.4.1 Establishment and Service of Central Database

Given the characteristics of the leather supply chain, leather production sites are responsible for the manufacturing and application of leather coatings, while pigment paste production and leather production are often

Figure 3: Schematic diagram of the central color Database

The central color database is designed with the following key features :

Firstly, the three databases, namely the leather coating line color database, the pigment paste product database, and the pigment paste development database, are accessible only to authorized users with modification permissions. Only with authorization can users partially

handled by separate enterprises, leading to a significant amount of technically confidential information that cannot be shared between them. To facilitate the consolidation of internal color data and enable efficient communication of color information across different nodes of the leather supply chain, a central color database can be established. This database comprises the leather coating line color database, the pigment paste product database, and the pigment paste development database (Figure 3).

access each other’s databases for reading purposes, in order to ensure undisturbed data integrity.

Secondly, to ensure the independence of data among several leather production ends using the same central database, different ports and data storage locations must be allocated.

Thirdly, beyond existing product information, confidential technical data are not exchanged between enterprises. The pigment paste laboratory color database is generally not accessible to coating production sites, and similarly, sensitive color matching information from leather production sites remains hidden from pigment paste producers.

4.4.2 Color Management of Global Collaboration Systems

Due to globalized production layouts, major enterprises may have production plants and R&D laboratories spread across the globe, supplying raw materials to downstream enterprises in various regions. For enterprises with factories in multiple regions, differences in process levels among different factories can lead to varying inter-batch color differences, directly affecting ÄE2 and ÄE5 in the color difference transmission chain. Therefore, each node in the leather supply chain must ensure batch consistency of products across different regional production sites. Serving as a communication platform, the central database allows leather producers to publish color difference requirements through the coating line color

Figure 4: Statistics of color difference data for various batches of pigment paste from different production sites of

the same enterprise before and after data chain integration

Leather trend colors and popular colors reflect public aesthetic preferences. Taking the automotive leather industry as an example, collaboration among pigment paste production end, leather production end, and OEMs

database, or to negotiate such standards with pigment paste production end. Based on these requirements, pigment paste production end issue finished-product inspection criteria for all factory products via the pigment paste product color database. Quality inspection laboratories and production departments then implement process controls according to these standards, with all production information transmitted entirely through the data chain. A similar approach can be applied to the finishing processes at leather production sites. By utilizing computers as data recording carriers, the efficiency of batch data traceability and the reliability of records are significantly enhanced.

As shown in Figure 4, two pigment paste factories (A and B) belonging to the same enterprise but located in different regions operated at different production process levels and followed distinct product standards before the integration of their data chains. Initially, Factory A’s process capability was markedly lower than that of Factory B, resulting in more severe fluctuations in product color difference. Through database consolidation and unified management, a consistent production process and product standard were established, gradually aligning the process levels of both factories to the same state.

facilitates the prediction of popular and trend colors, enabling early-stage color development and raw material preparation in advance. As one of the few direct channels for color information flow, the central database supports

the analysis to identify potential regional popular and trend colors through data exchange between the pigment paste product inspection database and the leather production line color database. On one hand, OEMs and leather production end directly communicate color requirements to pigment paste production end via the central database by placing orders. On the other hand, through quantitative research models and multivariate data analysis, OEMs and leather production end integrate data within the central database and subsequently provide feedback to pigment paste production end.

4.4.3 Traceability of Color Quality Issues Using Digitalization Technology

The preceding discussion primarily focuses on process control. When the control process fails and finished products have already been produced, discovering large scale quality issues at this stage means that problem tracing is often too delayed. Within the upstream and downstream supply chain, investigations initiated by a single party can rarely identify the true root cause. The key lies in joint traceability efforts across all nodes of the entire supply chain. At the current stage, although the central database cannot directly pinpoint the cause of a quality issue, it can assign a unique “data identity” to each color/batch, recording complete information such as chromaticity values, raw material batches, production batches, and measurement conditions. This ensures that all materials, processes, and inspection results at every stage of finished product manufacturing can be accurately matched, thereby providing essential data support for problem tracing.

5. Conclusion

From the acquisition of raw materials like pigment powder to the completion of finished product production at tanneries or OEMs, color difference continuously accumulates throughout the leather supply chain, ultimately potentially causing significant discrepancies between the finished product color and the target color. The color data

system strictly controls the cumulative value of color

difference at each node of the leather supply chain. The color data system constructs a new, efficient, stable, and traceable color management model, playing the following roles in leather supply chain color management and intelligent color matching: (1) At the pigment paste production end, color requirements from coating producers are transmitted directly to pigment paste manufacturers via the data chain. Pigment paste producers match and optimize their product lines using the R&D database, providing guidance for the development of new pigment paste products, facilitating color design closer to the target color at coating producers, and providing a data foundation for pigment paste producers to strictly control inter-batch color differences. (2) At the leather production end, the color data system significantly reduces the time required for color matching compared to visual observation and effectively lowers the probability of metamerism issues, improving R&D and production efficiency. (3) By deploying a reliable data chain and establishing terminal color measurement instruments and computer color matching systems, a complete and stable data chain will run through the leather supply chain, providing data for transmitting color requirements between different development ends, effectively reducing the color difference between finished leather products and the target color, and enabling more accurate achievement of the target color.

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