

Modern Translation of Industrial Heritage: Innovative Design and Practice of Traditional Enamel Craftsmanship in High-End Bicycle Components—Taking Tangshan Symbol as an Example

Huimin Luo

Department of Fashion Design, Tangshan University, Tangshan 063000, Hebei, China

Corresponding author: Huimin Luo (e-mail: luo11222622@163.com)

ABSTRACT This paper focuses on the contemporary expression of industrial heritage by taking Tangshan regional cultural symbols as the core and integrating traditional enamel craftsmanship into the design of high-end bicycle components. It addresses issues in current high-end manufacturing, including monotonous material texture, mechanized decorative expression, and insufficient regional cultural representation. The research is carried out in three stages. First, industrial elements and regional cultural symbols from Tangshan are extracted and abstracted to construct a translatable visual language system. Second, a process combining high-temperature fusion coating technology and metal surface pretreatment is used to develop enamel glaze formulas suitable for aluminum and titanium alloy substrates, with coating uniformity and adhesion optimized. Third, physical samples are tested and compared with traditional spraying processes in terms of wear resistance, corrosion resistance, and color stability. Experimental results show that the adhesion of improved samples S3 and S4 increases from 6.8 MPa to 9.4 MPa, the color difference decreases from 3.24 to 1.88, and salt spray resistance extends to 2.3 times the original value.

INDEX TERMS industrial heritage, enamel craftsmanship, tangshan symbol, material innovation, surface engineering

I. INTRODUCTION

BEING a significant cradle of modern Chinese industry, Tangshan has developed a unique regional industrial culture in its steel, ceramics, machinery, and pioneering technical production. In the modern context of high-end equipment manufacturing, the craft expression of this industrial heritage, including advanced fiber weaving and composite structures, is experiencing a loss of contact with contemporary functionality and symbolism. The conventional craft of enamel may hold some value to the treatment of surfaces in metals in that it has a unique glaze texture and weather resistance, although it is largely confined to the decorative sphere and has not reached a twin synergy of performance in the structure and cultural manifestation. Meanwhile, the contemporary production system is continually raising demands on lightweight materials, corrosion-resistance, and visual differentiation, which can only be fulfilled with difficulty by the utilization of coating technologies that do not imply any of the two previously mentioned methods, namely, mechanical spraying and electrophoretic

coloring [1-2]. Not only does this reuse of industrial heritage constitute a rediscovery of cultural resources, but it also carries along with it the reconstruction of design language and process adaptation.

This paper applies Tangshan symbols as a cultural artifact to investigate the new ways to use enamel craftsmanship in the high-end bicycle parts. The refinement of images by visual means, as well as morphological translation of industrial images of regions, is carried out, in which surfaces like railway tracks, the openings of furnaces, and ores are converted into textures of materials that can be identified in the structure of design. The enamel formula is modified by means of a combination of high-temperature melting technology and pretreatment of metal surfaces in order to provide the enamel with good adhesion and protective property at the functional level. The objective of the study is to develop a sustainable culture-craft-design integration model. By embedding these engineered techniques into traditional industrial heritage crafts, the model ensures that cultural symbolism achieves renewed technological utility

and aesthetic value [3-4].

II. RELATED WORK

Historical analysis of industrial heritage in product design and material remanufacturing has slowly morphologically reverted into craft regeneration. Studies available are concerned with visual representation of culture and duplication of the historical context, by redressing the lines of the regional textures, stylistic indicators, and narrative pictures to protract the type of conventional crafts in the modern environment. Nevertheless, since most of the industrial heritage crafts rely on unstable processes, including hand-firing and oxidation reactions, there are issues with their implementation in contemporary manufacturing systems, including low parameter controllability and incompatibility with structure [5-6]. Research on the combination of industrial symbols and product function has been carried out by both domestic and international scholars, the major problems of surface pattern transfer, micro-etching, and digital texture control, yet the research has largely not delved into the problem of the connection between the material, crafts, and culture.

The ancient fusion process of metals and glasses, enameling, has been used in art decoration, architecture, and in watchmaking, although there has been comparatively little research on how it can be used in structural components of high strength, or even in engineered components. Foreign researchers have advanced in the nano-silicate modification, the creation of low-melting-point glaze, and the control of oxidation and offer new concepts to the densification and functionalization of metal surface coating [7-8]. Domestic studies are more concerned with how to protect traditional enamel methods and digitalizing cultural heritage, and lack systematic methodological advice on how to innovate further. To fill this gap, integrating industrial heritage attractions with engineering design reasoning to create a measurable, manufacturable, and communicable design system is a new direction of cutting the loop of conventional crafts [9-10].

III. METHODS

A. EXTRACTION AND VISUAL LANGUAGE TRANSLATION OF INDUSTRIAL AND CULTURAL SYMBOLS IN TANGSHAN

Extraction of industrial and cultural symbols in Tangshan is mainly centered on industrial imagery including the smelting of coal and iron, firing ceramics and water transportation. Quantitative sampling and reconstruction of morphological features and color systems of them in a stylized form were done based on the integration of local cultural background and visual features of elements. The points of capture of the image chosen the texture of the steel mills, the rusty track of the railway and the gloss of the enamelware. There was high-resolution scanning and multi-angle illumination photography to create a set of parameters of color, reflectivity, and surface roughness.

The key geometric elements and color palette were also projected after digital layering processing, and the visual base was represented by reddish-brown, cobalt blue, and ivory white to reflect the industriality and minerality of the image of Tangshan. The visual translation applied a parametric morphological production approach, with the shape of intersecting tracks, flame curves and glaze cracks scaled to bicycle frame nodes, weld lines and texture areas on the coatings. 3D modeling software was utilized to give a proportional control to the linear and surface relationship so that the visual imagery of the culture could be perceived as being a part of the structure and not just an overlay decoration. The visual language translated into a surface style of the elements is mechanical force combined with cultural image, which offers the material memory of industrial legacy to be exposed in the environment of modern goods in terms of concrete tactile experience and gloss, thereby facilitating the fusion of craft aesthetics and engineering design.

B. INNOVATIVE DESIGN OF ENAMEL CRAFTSMANSHIP

The new design of the enamel process depends on the thermal expansion corroboration of the metal substrate and the enamel glaze. Once the surface composition test has been done, the thickness or the phase structure of the oxide layer in the oxide-coated aluminum and titanium alloy substrates is adjusted to minimize the concentration of thermal stress during the high temperature melting. The surface of the aluminum alloy is subjected to alkaline activation and micro-arc oxidation in which a microporous oxide film is created which promotes the mechanical adhesion of the enamel glaze. A mixture of electrochemical polishing and inert atmosphere oxidation of the titanium alloy to form appropriate roughness and surface energy interface enhances the stability of the glaze adhesion reaction. The glaze formulation is based on a silicate system, with adjustments to the ratio of SiO_2 , B_2O_3 , and Na_2O to control the melting point and fluidity, ensuring good wettability and transparency within the 860–890 °C range. The addition of trace amounts of ZrO_2 and CoO achieves integrated strengthening and coloring effects. Gradient heating and slow cooling are used during the melting process, combined with infrared thermography to monitor the glaze spreading state and prevent thermal cracking and bubble deposition. Table 1 shows the relationship between enamel process parameters and substrate compatibility.

TABLE 1. Enamel Process Parameters and Substrate Compatibility

Substrate type	Pretreatment process	Oxide layer thickness (μm)	The main component ratio of the glaze ($\text{SiO}_2\text{:B}_2\text{O}_3\text{:Na}_2\text{O}$)	Melting temperature range ($^{\circ}\text{C}$)	Cooling method
aluminum alloy	Alkali activation + micro-arc oxidation	8–12	6:2:1	860–880	Slow air cooling
Titanium alloy	Electrochemical polishing + inert oxidation	10–15	7:1.5:1	870–890	Controlled cooling
aluminum alloy	Alkali activation	5–8	5.5:2.5:1	850–870	Rapid cooling
Titanium alloy	Inert oxidation	8–10	6.5:2:1	880–900	Slow air cooling
aluminum alloy	Micro-arc oxidation	9–11	6:2:1	860–880	Water bath cooling
Titanium alloy	Electrochemical polishing	7–9	7:2:0.8	870–885	Stable cooling

The parameters in the table are used to guide the compatibility between different substrate surface treatment methods and glaze ratios to ensure the integrity of the ceramic layer structure and color stability.

C. PROTOTYPE MANUFACTURING AND EXPERIMENTAL DESIGN

The prototypes were manufactured using high-end bicycle load-bearing components, with sample blanks achieving a geometric accuracy of 0.05 mm obtained through precision CNC machining. The coating area and thickness distribution were determined based on the frame nodes and stress distribution. The coating application process employed electrostatic spraying combined with directional heating to create a uniform coating layer on the metal surface. The heat treatment process was completed in an argon-protected furnace, with a heating rate controlled at $5^{\circ}\text{C}/\text{min}$. Melting and holding time was equated with the type of substrate to stabilize the interface diffusion. To avoid the problem of cracking of the ceramic layer on account of thermal stress during the cooling process, a programmed cooling curve was applied. The digital microscopy was used to test the continuity and boundary of the enamel layer in the completed prototypes. The experimental design involved three process systems as variables, where three different varieties of prototypes were set, namely; traditional spraying, standard enamel, and improved enamel. The experimental conditions included corrosion resistance, abrasion resistance and color retention tests. All the samples of tests were prepared and stored in the same environmental pressure and humidity to make all the samples comparable and stable. Sample numbers were randomly assigned, and the testing sequence was executed in a double-blind manner to eliminate human bias at the operational level.

IV. RESULTS AND DISCUSSION

A. ANALYSIS OF PROCESS EFFECT AND VISUAL REPRESENTATION

Pull-off method was used in testing adhesion. The surfaces were wiped with acetone to clean them after the standard-size cutting was done. The adhesive parts of the bonding were bonded to the loading head with epoxy. A vertical tensile test was done after the sample cured at room temperature, 24 hours. To assess the maximum value of stress of the interface at the peeling point, the tensile rate was

adjusted to 1 mm/min and load-displacement curve was plotted using electronic universal testing machine. Testing was conducted on color difference using a spectrophotometer. The tool adopted the CIE Lab+ color space, and, three-point measurements were made, and the mean value was obtained. To control the effect of environmental variables on the color indicators, samples were loaded with a 72 hours constant temperature/humidity factor and then the test was performed to eliminate the effects of environmental variables in such that samples of the same process produced the same color indicators under consistent lighting and angle factors. Table 2 shows the test results.

TABLE 2. Results of Enamel Layer Adhesion and Color Difference Tests

Sample number	Coating process type	Adhesion (MPa)	Color difference value ΔE	Surface observation features
S1	Traditional spraying	6.8	3.24	Uneven color distribution, localized cracking
S2	Standard Enamel	8.1	2.15	Stable luster, micropores visible
S3	Improved Enamel	9.4	1.88	The surface is dense and the reflection is uniform.
S4	Improved Enamel	9.3	1.91	Smooth and dense, with no obvious defects
S5	Standard Enamel	8.0	2.23	Slight color differences are perceptible in some areas.

The better process samples S3 and S4 demonstrated much better adhesion, surface structural integrity, and stronger interfacial cohesion strength. The adhesion improved by about 38 percent with a difference in color as 6.8 MPa to 9.4 MPa and the color difference reduced by about 42 percent as compared to 3.24 to 1.88 which showed that the uniformity of the melts improved. The surface was well-glossed with sustained-high gloss and uniform surface reflection, and the layer of glaze had higher continuity of the glass phase which minimized the risk of microcracks and color drift. On the whole, they were stable and aesthetically consistent, and the effects of process optimization under the impact of the improved process were substantiated in the functional and aesthetic aspects.

B. PERFORMANCE TEST RESULTS

Salt spray resistance tests were conducted according to GB/T 10125 standard. After cleaning and drying, samples were placed in a neutral salt spray chamber. The reagent was prepared using a 5% NaCl solution, with the pH value controlled between 6.5 and 7.2. The spray pressure was maintained at 1 bar, the atomization rate at 1.2 mL/80 cm²·h, and the chamber temperature was kept constant at 35 °C. The test cycle was 24 hours per detection unit, and the surface gloss, color changes, and corrosion product formation of the coating were observed periodically. After the experiment, the surface corrosion depth and peeling range of the samples were examined using a 200x optical microscope, and the corrosion area ratio was quantified using image analysis software. Failure time and corrosion characteristics were recorded for each group of samples after the same exposure time. Data were averaged from three repeated experiments, as detailed in Table 3.

TABLE 3. Salt Spray Resistance Test Results of Enamel Coating

Sample number	Coating type	Failure time (h)	Corrosion area percentage (%)	Surface condition description
S1	Traditional spraying	240	36.2	Glaze peeling and obvious oxidation of the substrate
S2	Standard Enamel	420	18.7	Localized corrosion spots appeared
S3	Improved Enamel	550	11.3	The surface is intact, with no obvious discoloration.
S4	Improved Enamel	565	10.8	The glaze is continuous with slight pitting at the edges.
S5	Standard Enamel	430	19.4	Uniform color, with localized salt crystal deposits

Experiments showed that the failure times of the improved enamel samples S3 and S4 were 550 h and 565 h, respectively, which is approximately 2.3 times longer than that of the traditionally sprayed samples. The corrosion area ratio decreased from 36.2% to 10.8%, indicating that the enamel densification process significantly inhibited chloride ion penetration. The surface remained glossy and showed no signs of structural disintegration, and no pinhole corrosion was observed in the interface bonding area. Therefore, the novel formulation and heat treatment process effectively improved both protective continuity and ion barrier performance, providing strong support for the durability of the coating structure.

C. IMPROVEMENT MECHANISM ANALYSIS

The enhanced process is mainly attributed to synergistic effect of interfacial microstructure and chemical composition of the glaze. Adjusting the components in the glaze

that form the network of the glass phase provides the glaze with increased wettability and diffusion in the molten state, enhancing the (uniformity of the) spread of the molten glaze on the metal surface. The micro-arc oxidation and electrochemical polishing processes produce a gradient roughness surface morphology on the substrate and enhances the interfacial contact area, and provides good mechanical bonding sites. At the melting phase, the rate of heating is carefully monitored to decrease the disparity in the thermal expansion coefficients of the glaze and the substrate, and thus, to reduce cracking in the glaze due to the stress concentration during the rapid cooling process. The interface produces a solid transition zone of the metal oxide which in turn allows chemical bonding between inorganic silicate network and the substrate without delamination due to mechanical adhesion as is the case with traditional processes. This has contributed to the stability of color and gloss by rebalancing flux and coloring ions in the glass phase giving the even pigment dispersion at high temperatures without precipitation to making sure the structure becomes dense and the coating of color remains long lasting. The net action constitutes a simultaneous optimization of material chemistry and thermal characteristics, which provide the enamel layer with structural stability and aesthetic appearance.

V. CONCLUSION

This research presents a multi-dimensional convergence of industrial heritage craftsmanship and advanced composite engineering, integrating enamel with high-strength fiber reinforcement in high-end bicycle parts. Beyond superficial coating, this synergy creates a design system that unifies structural functionality with the visualization of engineered woven textures and traditional aesthetics. By means of the abstract translation of industrial symbols of the Tangshan area, a material surface language of the regional identity is created, which guarantees the integrity of the artistic semantics and engineering performance. During the process innovation step, both chemical composition of the enamel and the surface reaction properties of the substrate are precisely aligned which enhances the consistency of interfacial bonding and interlayer stability, which shows the regenerative capability of industrial heritage in designing new materials. Work in design indicates that the modern manifestation of traditional artisanship is not only a formal innovation, but also a manifestation of the harmony between the tactile warmth of craftsmanship and the rationality of industry. The existing studies are not yet complete over metal systems and single work pieces; optimization of parameters has not yet been done regarding response laws in complex stress conditions. Future studies can extend the analysis of multi-material composites and long-term service performance by investigating the integration of high-performance technical with enamel within intelligent production systems. This cross-border application of advanced fiber-reinforced structures will explore how cultural products can evolve through the synergy of traditional craftsmanship

and modern material engineering.

AUTHOR CONTRIBUTIONS

Huimin Luo designed, collected and analyzed the data, and drafted the manuscript. Huimin Luo conducted the study, critically revised the manuscript for important intellectual content, and gave final approval of the version to be published. Huimin Luo participated fully in the work, take public responsibility for appropriate portions of the content, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

CONFLICTS OF INTEREST

The author declares no conflict of interest.

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