

Research Progress of Laser Induced Metal Surface Coloring Technology

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ABSTRACT

Laser-induced metal surface coloring technology combines the advanced manufacturing technology of modern laser technology and material science. It no longer relies on dyes or chemicals to achieve material surface coloring, but makes use of the characteristics of the interaction between laser and metal materials. Through the precise control of laser parameters (such as wavelength, pulse width, energy density, etc.), complex micro-structures can be formed on the metal surface, thus changing its optical properties. To achieve the coloring effect, compared with the traditional coloring method, it has significant advantages such as no pollution, high precision, strong flexibility and so on. This paper deeply discusses the core principle of laser-induced metal surface coloring, systematically analyzes the evaluation criteria of coloring quality, and focuses on the key factors affecting the induced coloring process. Despite its strong application potential, laser-induced metal surface coloring technology still lacks sufficient key data support for constructing an accurate coupling model between laser parameters and coloring effect. This hinders the achievement of high controllability, reproducibility, durability, and stability of surface shading colors. Therefore, it is necessary to further focus on these core issues and accumulate more experimental data through fine experimental design and advanced characterization technology, so as to promote the continuous optimization and wide application of laser-induced metal surface coloring.

KEYWORDS

Laser-induced coloring; Coupling model; Controllability and Reproducibility; Durability and Stability

1. INTRODUCTION

With the promotion of globalization and digital economy, product safety, anti-counterfeiting authentication and supply chain transparency have become the key issues to be solved in the field of industrial manufacturing. In the face of the local limitation of traditional surface treatment technology in the face of personalized and diversified requirements, laser-induced metal surface coloring technology is gradually establishing its leading position in the field of surface treatment because of its unique characteristics of high efficiency, environmental protection and high precision. As a cutting-edge innovation in the field of laser processing, the core mechanism of this technology relies on the fine interaction between laser and materials, and realizes the accurate coloring and marking of metal surface by skillfully adjusting laser parameters, which is not limited to the improvement of visual aesthetics. It also contains the far-reaching significance of strengthening product safety and traceability.

Synergistic effect between laser and material: from thermal effect to photochemical evolution, the core is to make use of the interaction between laser beam and metal surface to precisely control the energy density and pulse width of laser to cause the instantaneous temperature rise or chemical bond recombination of material surface, so as to realize the controllable modification of material surface properties [1]. This process is not only limited to the single dimension of thermal effect, but also involves the multi-level development of photochemical reaction, which gives unprecedented color and texture to the material surface [2]. By fine-tuning the laser parameters, the precise manipulation from macro to micro scale can be realized to ensure that the formation of the marker not only meets the aesthetic requirements, but also ensures the structural integrity and functionality of the material.

The multi-dimensional advantages of laser processing technology: from material compatibility to processing accuracy, the reason why laser processing technology can stand out in modern manufacturing lies in its universality to a variety of solid materials, including but not limited to metals, semiconductors and polymers. The high energy density of the laser beam means that the heat-affected zone is strictly limited, which effectively avoids the potential damage to the untreated area of the material, which is very important to maintain the overall performance of the material. Coupled with the micron or even nanometer machining accuracy brought by the laser focusing ability, laser processing shows an excellent ability to surpass the traditional processing technology in realizing the construction of complex geometric structures and fine patterns [3]. Together, these advantages create the core competitiveness of laser processing in modern manufacturing, especially in the field of high-end manufacturing in pursuit of extreme personalization and high efficiency.

2. THE BASIC PRINCIPLE OF LASER-INDUCED METAL SURFACE COLORING

The principle of laser-induced metal surface coloring technology (the scheme of color laser marking system shown in Fig.1) and its coloring mechanism are more complex, mainly through the interaction between laser and metal materials, resulting in a series of physical and chemical changes on the metal surface, thus changing the optical properties of the surface. The surface of metal shows different colors, and its coloring principle and mechanism include the following aspects:

Laser Induced Periodic Surface Structure(LIPSS): When the laser beam hits the metal surface, the high energy density laser will heat and melt the metal surface instantly. On the molten metal surface, due to the interference effect of surface tension, plasma pressure and laser field, a regular periodic fringe structure is formed. Its structure is similar to a grating, which can diffract the incident light, causing the light of a specific wavelength to be enhanced or weakened, resulting in a color effect. This method is environmentally friendly, does not need to use any chemical reagents, and the periodic structure produced has the advantages of long-term stability. Because of its environmental protection and persistence, LIPSS technology shows great application potential in the field of metal surface coloring, which can achieve color diversity and design customization, while maintaining the original physical properties of materials. Liu [4] et al proposed the laser-induced periodic surface structure and the physical mechanism and evolution of laser-induced nanoparticles and nanostructures, and optimized the generation and color regulation of LIPSS by numerical simulation and experimental observation.

Thin film interference caused by surface oxide layer: laser treatment can also form a thin oxide layer on the metal surface. The different thickness of the prepared oxide layer will lead to interference in the reflection and transmission of light at the interface, and then change the light spectrum of reflected light. The mechanism of color change involves utilizing the high energy density of the laser as an efficient heat source to rapidly heat the metal surface. Trigger the chemical reaction between the metal and the oxygen in the surrounding air to form a colored oxidation film. By adjusting the processing parameters of the laser, the thickness and composition of the oxide film can be accurately controlled, and then the color performance can be affected. The physical properties of the film cause

the light to interfere with the film when it comes into contact with the metal surface, which leads to the color phenomenon on the metal surface. Li et al [5] analyzed the formation of oxide layer during the interaction between ultraviolet laser beam and stainless steel in air, and used YVO4 laser with wavelength 355nm to scan stainless steel samples in air. The laser scanning speed should have a significant effect on the initial oxidation, and the slow scanning is helpful to form the oxide layer with double-layer structure. With the increase of laser scanning times, the thickness of oxide layer increases, but the growth rate slows down gradually, which may be due to the increase of diffusion distance and the formation of microcracks at the interface between oxide and substrate metal.

The phase transition between (Surface Plasmon Resonance, SPR) and metal surface materials shows far-reaching significance and application potential in the field of modern optics and material science. When the high-energy laser beam is precisely focused on the metal surface, it carries enough energy to induce the formation of nano-scale particles or clusters on the metal surface. These tiny and delicate nanostructures can carry and amplify a unique physical phenomenon-surface plasmon resonance, that is, the collective oscillation effect of free electrons on the metal surface, that is, it shows strong absorption and scattering properties for photons in a specific wavelength range. Thus, the metal surface presents a distinct and specific color expression, which gives unprecedented dimension and depth to the optical properties of the material. Secondly, the thermodynamic effect of laser irradiation technology on the metal surface can not be ignored. Under the action of the instantaneous high temperature of the laser pulse, the local area of the metal surface can quickly reach the extreme temperature condition, which promotes the phase transformation of the internal structure of the material. The phase transformation mechanism can guide the metal to transform from the original crystal phase or ordered arrangement to a new crystal phase structure, and even form an amorphous disorder structure. Therefore, the novel structures derived from phase transition are often accompanied by fundamental changes in optical properties, such as subtle fluctuations in refractive index and significant differences in absorption coefficients, thus profoundly affecting the spectral response characteristics of metal surfaces [6, 7].

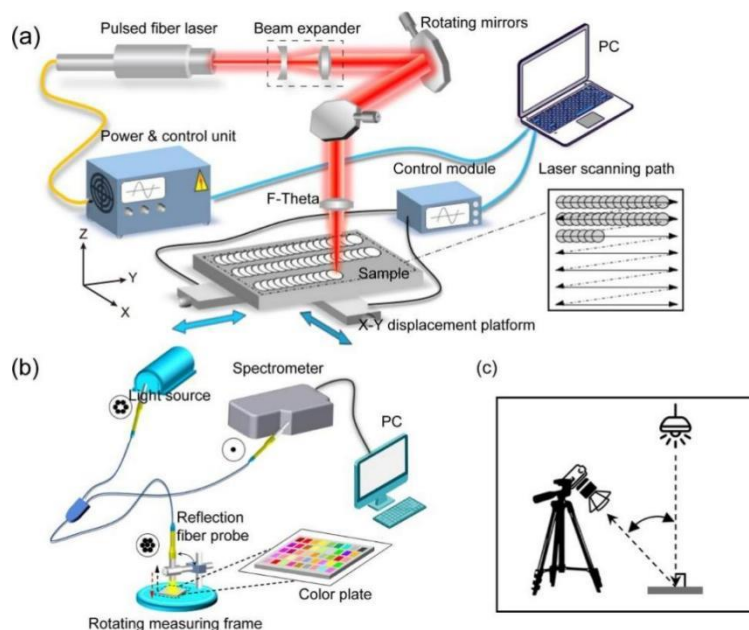


Figure 1. (a) The principle scheme of color laser marking system, (b) configuration of the color measuring system and (c) schematic diagram of sample photo acquisition [8]

3. LIMITATION AND QUALITY EVALUATION OF LASER-INDUCED COLORING

3.1. Limitations of Laser-Induced Coloring

Due to its unique surface treatment capabilities, laser-induced coloring technology has garnered significant attention. However, its reproducibility and stability in practical applications have emerged as pressing issues requiring urgent resolution. Therefore, relevant researchers have carried out a series of studies on this problem. Veiko et al [9] developed a complete color palette based on the reflection spectrum, which is specially designed for a 1.06 μm nanosecond pulsed fiber laser, which can obtain any color within a limited area of color coordinates. Roozbahani et al [10] developed a chromatography containing fifteen different colors. The repeatability of the chromatography was evaluated by reflection spectroscopy. All colors except one specific color showed a high repetition rate. Although the coloring method based on reflection spectrum has improved in stability and repeatability, it still needs to be strengthened in terms of environmental adaptability. Antonczak et al [11] deeply studied a variety of process parameters that affect the color repeatability of AISI 304 stainless steel and titanium, including laser power, pulse frequency, scanning speed and line spacing, and revealed how these parameters fine regulate the color generation process, which provides a theoretical basis for more accurate color control. The fine control of process parameters such as laser power, pulse frequency, scanning speed and line spacing is very important to achieve the desired coloring effect, but the optimal combination of these parameters and the mechanism of interaction with materials is still a technical problem. In addition, the effect of laser-induced coloring may be affected by environmental conditions, limiting its stability and reliability in extreme or changing environments. Luo et al [12] studied its effect on the formation of microstructure and nanostructure on the surface of stainless steel from the point of view of gas ring, and further pointed out that the gas environment has a significant effect on the final color performance. Cucerca et al [13] proposed an innovative data-driven laser marking system, which uses color discovery algorithm to simulate the manufacturing process of black box, which provides a new possibility for the versatility of laser color marking. However, this method still requires further exploration to propose an effective solution for addressing the repetitive issue of coloring effects across different substrates, posing a significant challenge in achieving consistent coloring. Odintsova et al [14] improved the repeatability and stability of color excited light labeling technology under corrosive conditions, and its research deeply discussed the problem of color stability, especially in the aspects of chemical resistance and environmental resistance, which provided a new angle of view for color laser marking on titanium, that is, the problem of color stability was considered from the point of view of chemical resistance and environmental resistance. It has been demonstrated that laser color labeling on titanium surfaces exhibits high durability against chemicals like salts and acids, and is tolerant to high-temperature and humidity environments.

To sum up, although laser-induced coloring technology has achieved good performance in specific laser systems, its universality and stability in different environments and substrates are still facing challenges. It is also necessary to overcome the limitations of current technologies in environmental adaptability, repeatability and stability, color control accuracy and process parameter optimization. Future research work should focus on developing more robust coloring methods, improving the controllability of process parameters, and exploring new technical means to achieve more extensive applications and higher quality coloring effects.

3.2. Evaluation of Color Stability

The color difference evaluation parameter ΔE_{ab}^* is an index used to quantify the visual difference between two colors. It is defined in the CIE Lab color space. ΔE_{ab}^* is set to a three-dimensional Euclidean distance, mainly considering the differences in color luminance (L^*), red-green axis (a^*)

and yellow-blue axis (b^*). However, ΔE_{ab}^* is not a perfect color difference formula such as formula (1), which ignores the nonlinear characteristics of human eyes' perception of color. In order to improve this, a more complex color difference formula, such as CIEDE2000 (ΔE_{00}), is later proposed, which takes into account the visual adaptability of the observer, thus providing a more accurate assessment of color differences. However, compared with the traditional colorization methods, laser color marking still has challenges in terms of reproducibility and stability, which makes it difficult to find a suitable reference color. In order to overcome this problem, Fig. 2 proposes a color stability evaluation method, which does not depend on the reference points, but evaluates color stability in all parameter spaces.

$$\Delta E_{ab}^* = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (1)$$

$$\begin{aligned} \Delta L^* &= L_2^* - L_1^* \\ \Delta a^* &= a_2^* - a_1^* \\ \Delta b^* &= b_2^* - b_1^* \end{aligned} \quad (2)$$

Where L_1^*, a_1^*, b_1^* is the coordinate of the reference color in the Lab* space, and L_2^*, a_2^*, b_2^* is the coordinate of the test color.

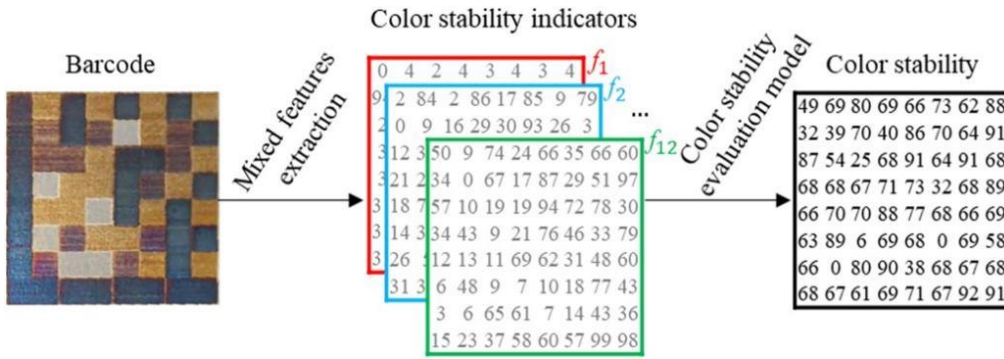


Figure 2. Color stability evaluation method of a direct laser color marking of barcode [15]

Antonczak [11] emphasized the effect of temperature on the repeatability of laser-induced coloring. The effect of temperature on color was studied systematically by using spectrometer and CIE color difference parameter ΔE_{ab}^* . As shown in Fig.3a, the color stability is significant with the increase of temperature. Fig. 3b and Fig.3c show the visual colorimetric results based on L^* , a^* , b^* parameters and the total color difference ΔE_{ab}^* as a temperature function, respectively. By comparing the test color with the reference color shown in Fig.3b, it is found that except yellow, the other colors do not change much in the whole temperature range. Geng et al [15] further studied the effect of scanning speed on color. Fig. 4 shows the trend of color change at different scanning speed, especially pointing out that yellow has the highest stability at 150mm/s. This discovery is a great significance for optimizing the laser-induced coloring process.

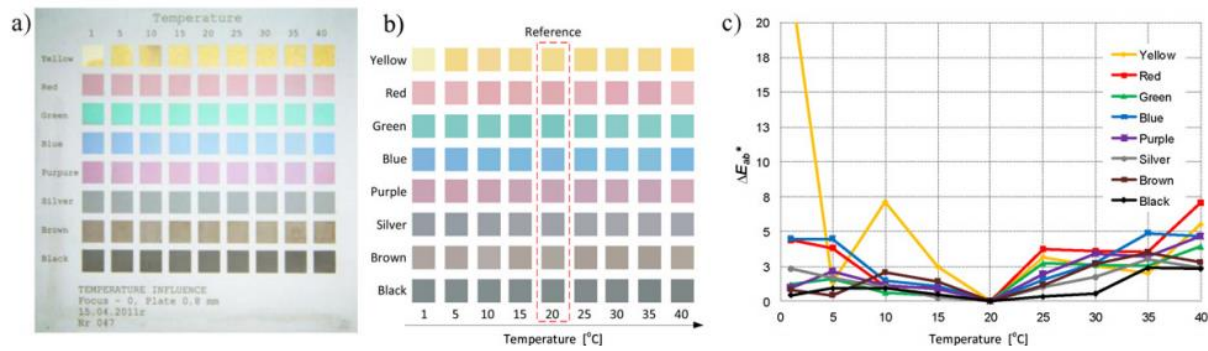


Figure 3. The influence of initial temperature of the material on the obtained colours: (a) photo of the test sample, (b) the colour palette created on the basis of colorimetric measurements and (c) graph of the ΔE_{ab}^* parameter [11]

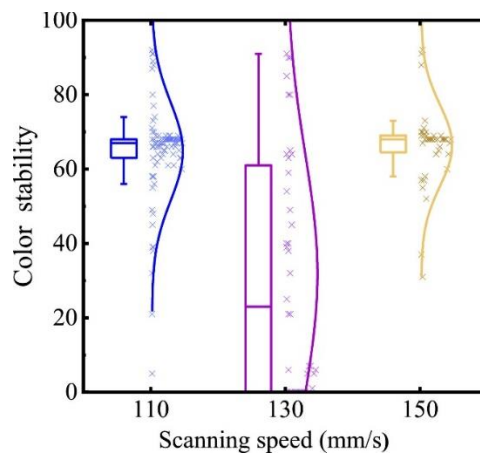


Figure 4. Color stability distribution (boxplot + normal curve) of cells at the scanning speeds of 110 mm/s, 130 mm/s, and 150 mm/s on Ti6Al4V [15]

3.3. Stability Mechanism of Laser-Induced Coloring

In the process of laser-induced coloring, the stability of surface color is affected by many factors, among which the thin film interference effect of surface oxidizing layer is particularly important. It is worth noting that the temperature distribution has a significant effect on the formation of the oxide film thickness, while the slight change of the oxide film thickness is directly related to the stability of the final color. Therefore, in-depth understanding and control of these factors is very important to improve the quality of laser-induced coloring. Geng et al [15] made an in-depth analysis of how temperature and time affect color stability in the process of laser-induced coloring by introducing a full-parameter space color stability evaluation method. This study provides a new and unique perspective for a better understanding of the internal mechanism of color stability.

In the study of laser-induced coloring, the mechanism of color generation mainly focuses on two directions: one is the dynamic change of oxide thickness [16, 17], and the other is the change of material composition induced by laser [18–20]. The study of Amara et al [1] revealed that the thermal oxidation process is the dominant mechanism of color formation under the action of nanosecond pulsed laser, in which the thickness of the oxide layer plays an important role in the formation of multiple spectra. Yang et al [21] further discussed the growth mechanism of metal oxides during nanosecond laser irradiation. Not only the oxidation reaction rate was measured, but also the sequence of continuous formation of different oxide layers was analyzed. On the other hand, Lu et al [22] focused on the mechanism of oxide composition in color formation, revealing the close relationship between color and the fractal formation of different oxides. In addition, the study of Luo et al [12]

emphasized the critical influence of different gas environments in the process of color formation, highlighting the significant effect of environmental factors on the effect of laser color marking.

Based on the above research, it can be concluded that surface oxidation is the main cause of color in nanosecond pulse laser color marking. However, in the application scenario of femtosecond pulse laser marking, the diffraction effect resulting from the surface ripple structure may constitute another significant mechanism for color generation. These findings not only deepen the understanding of laser-induced coloring process, but also provide valuable reference experience for further optimization of excited color labeling technology. Although the current research has deepened the understanding of the luminous color labeling process to some extent, in exploring the comprehensive test and mechanism of the synergistic effect of oxide composition and oxide film thickness on the color formation process, there are still deficiencies and gaps in the theoretical research basis. In addition, the current literature is still insufficient in fully revealing how color changes further affect the surface properties, ablation depth and mechanical hardness of materials. To address these research gaps, it is imperative to comprehensively consider the combined effects of oxide composition, oxide film thickness, and environmental factors on the color generation process, thereby gaining a profound understanding of laser-induced coloring and enhancing its stability and reliability.

4. INFLUENCE FACTORS OF LASER-INDUCED METAL SURFACE COLORING

The effect of color laser induced coloring technology is affected by multiple complex factors, including the chemical composition and physical properties of materials, surface finish, and different laser process parameters. Specifically, the working mode of the laser, the wavelength of the laser, the pulse width, the power, the repetition rate, the scanning speed and the amount of defocus determine the quality of the induced coloring process and the final coloring effect. Among these factors, the interaction between different wavelengths of laser and materials is particularly important, which directly affects the depth and range of thermal effect. At the same time, the pulse width determines the time scale of energy input, which affects the transient characteristics of thermal effect. Li's research [23] provides a new perspective, suggesting that femtosecond lasers of different wavelengths can induce different types of ripples on stainless steel surfaces, thus producing completely different colors. This discovery not only broadens the understanding of laser-induced colouring technology, but also provides a new controllable parameter for peer researchers to produce diverse color effects.

Roobahani et al [10] discussed in depth the significant influence of laser processing parameters, including scanning speed, pulse duration, output power and pulse repetition rate, on the surface color formation of materials. The study revealed that although the direct effect of the increase in laser power density on the color change was not significant, it did prompt the parameter window to shift towards higher scan speed values. At low scanning speed, the color is mainly dark gray. As the scanning speed increases, the color sequence gradually changes to dark green, dark purple, Burgundy, orange, light green, gold, and then light blue. Especially at high frequencies, certain colors such as light pink, ruby green, or bright purple appear. However, at a frequency of 1000 kHz, all scan speeds uniformly form a silver color, failing to form a multicolor window.

Similarly, the impact of pulse duration on the color effect can not be ignored, the study found that the color generated by the longer pulse duration is not only more shiny, but also smoother; However, the short pulse duration results in a shift of the parameter window towards lower scanning speeds, thereby diminishing the marking efficiency. As shown in Fig.5, Fig.6, Fig.7, and Fig.8, these phenomena are visually demonstrated. Geng et al [15] used a nanosecond laser to mark bar codes directly on the surface of Ti6Al4V and 304 stainless steel, and thoroughly analyzed the influence of cell edge, cell area and scanning speed on the color stability of laser marking. By simulating the temperature distribution of 304 stainless steel surface heated by laser, it is found that the combined effect of temperature and time makes the color stability fluctuate periodically with the increase of scanning

speed. Among them, the color with larger relative temperature difference has lower stability, while the color with smaller relative temperature difference shows higher stability, which reveals the direct influence of laser processing parameters on the thermal effect and physical changes in the coloring process. Xiang et al [8] reported for the first time the phenomenon of color-mixing labeling of samples irradiated by nanosecond pulse laser, which not only enriched the theoretical basis of laser-induced coloring, but also provided new possibilities for achieving diversified color effects. By systematically studying the effects of average power and scanning speed on color change, and precisely controlling these parameters, Xiang et al. A wide range of colours is successfully achieved on the SUS304 stainless steel plate. In order to further understand the mechanism of laser-induced coloration, the surface morphology and phase composition of laser-induced mixed coloration samples were analyzed in detail by field emission scanning electron microscopy (FESEM), energy dispersive spectroscopy (EDS) and X-ray diffraction (XRD). These studies not only significantly enhance the understanding of laser-induced coloring mechanism, especially in revealing the complex relationship between oxide film thickness and injection energy, but also provide valuable guidance for optimizing laser-induced coloring process, which is of great significance for achieving more accurate and stable coloring effects.

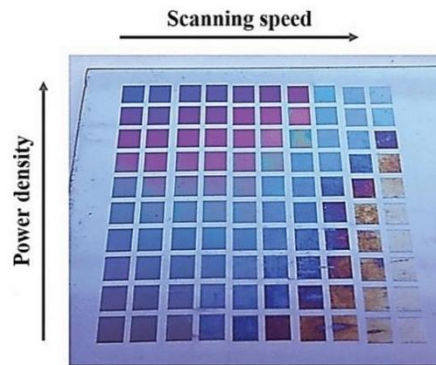


Figure 5. The dependency of produced color on the power densities vs scanning speed [10]

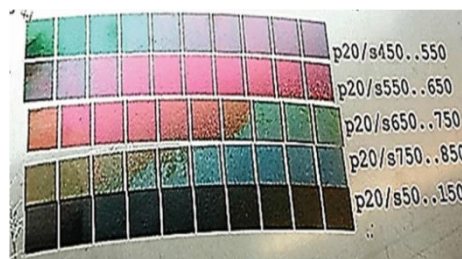


Figure 6. The dependency of produced color on the scanning speed [10]

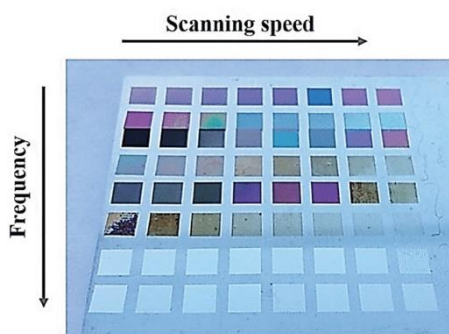


Figure 7. The dependency of produced color on the scanning speed for various frequencies [10]

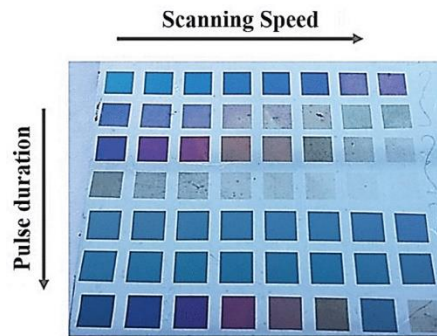


Figure 8. The dependency of produced color on the scanning speed for the various pulse durations [10]

By optimizing laser processing parameters, Voisiat et al [24] successfully produced a direct laser interference pattern with a periodic array of holes on the surface by using a 70 ps pulsed laser source with a wavelength of 532 nm, the uniformity of structural color on stainless steel was significantly improved. This study demonstrates the potential to significantly improve color uniformity by precisely controlling laser parameters. Huang et al [17] used picosecond pulsed laser to achieve coloring of various colors on the surface of Ti-6Al-4V (TC4) alloy, which conforms to the standard CMYK color mode. By means of SEM and EDS, it is revealed that the color is caused by the oxide layer formed on the surface of TC4. This study not only elucidates the internal relationship between laser energy, processing parameters and coloring results, but also further explains the limiting effect of hue on saturation. Under the premise of appropriate laser energy, by adjusting the scanning speed and scanning distance, the joint impact of the two parameters makes the pattern generated on the surface of TC4 alloy show more rich color changes, which fully shows that laser induced metal surface coloring technology is a complex process involving multi-parameters and multi-effects. Ma et al [25] focused on the influence of scanning speed and scanning distance on the surface color of SUS304 stainless steel, and the lower scanning speed and smaller scanning distance are conducive to the production of dark surface, and then obtain a brighter color film. The change of scanning speed directly affects the residence time of the laser on the surface of the material, and then affects the size and shape of the heat treatment area. Liu Zhongming et al [26] studied the temperature field generated by laser pulses on the surface of materials through calculation and simulation, and deeply analyzed the influence of different laser parameters on the temperature field during the induction coloring process and the relationship between the temperature field and the color effect. The research shows that: The laser process parameters can shape the induced coloring result by acting on the thermal effect, and diversified parameter configurations can achieve the same color effect, which provides an important theoretical support for the optimization of laser induced coloring technology.

To sum up, laser-induced metal surface coloring technology is a complex process involving multi-parameters and multi-effects. By precisely regulating the average laser power, scanning speed, scanning distance and other core parameters, accurate control of metal surface color can be achieved. In this process, the formation of oxide film and the thickness of film layer play a decisive role in the final coloring effect. At the same time, the influence of laser parameters on the temperature field and the close relationship between the laser parameters and the color effect provide a solid theoretical basis for realizing the specific color effect.

5. APPLICATION PROSPECT OF LASER INDUCED COLORING TECHNOLOGY

With its non-contact, high precision and excellent adaptability, laser-induced metal surface coloring technology has shown remarkable potential in the manufacturing field. Compared to traditional electrochemical and mechanical labeling methods, laser-induced coloring technology does not

require mechanical pressure, thus ensuring the integrity and original accuracy of the material, which gives it a significant advantage. The technology is adaptable and can handle almost any type of material. Specifically, solid-state lasers are particularly suitable for the coloring of metal materials, while gas lasers have excellent processing capabilities for non-metallic materials, and their broad adaptability enables laser-induced coloring technology to cover a wider range of manufacturing application scenarios. It is worth mentioning that laser-induced coloring technology can be seamlessly integrated with advanced technology such as machine vision to build a highly efficient automated processing solution. Its integrated technology not only meets the high requirements of modern manufacturing for flexibility and intelligence, but also greatly improves the processing accuracy and speed. This further enhances its core competitiveness in the manufacturing industry.

Cao Xuelu et al [27] explored the application of image processing technology in the field of laser-induced coloring, and used Photoshop software to transform colorful images into clear black and white patterns to adapt to the laser-induced coloring process, thus achieving personalized coloring effects. Combined with machine vision technology, this process not only improves the accuracy of the coloring position, but also significantly increases production automation and overall efficiency. Keyens [28] has made significant progress in the field of laser engraving with its MD-X series three-axis hybrid laser engraving machine, which integrates cutting-edge autofocus and positioning functions to ensure consistency and accuracy of laser-induced staining even when dealing with tilted surfaces. Further, the system is equipped with a real-time monitoring mechanism, which can continuously monitor the operating status of the equipment, effectively ensure the quality stability of the induced coloring, and lay a solid foundation for the industrial application of laser coloring technology.

Although laser-induced coloring technology has made significant progress with the assistance of integrated machine vision systems, technical challenges remain, especially for precise positioning of specific types of workpieces. For example, the positioning system developed by the Mayo team is excellent at handling straight contour workpieces, but its positioning accuracy needs to be improved for workpieces with large thickness or complex shapes. This highlights the need for further research and technological innovation in the field of machine-assisted laser-induced coloring to overcome existing limitations and expand the application boundaries of the technology. Against this background, Shan Tao et al [29] devoted themselves to solving the quality detection problem in the laser-induced coloring process has been refined and made significant contributions to enhancing the consistency and reliability of the coloring process: Through the fine analysis of the image characteristics of the workpiece, the induced coloring process is optimized, and the pain points in the actual operation are directly calibrated. Firstly, the high precision checkerboard is used to calibrate the camera to ensure the accuracy of the image acquisition. Then, the contour based template matching algorithm is used to accurately locate the relative position and rotation Angle of the workpiece and the standard template, so as to calculate the exact coordinates of each induced coloring point on the workpiece, which significantly improves the accuracy of the coloring position. Meanwhile, the common defect types in the process of laser induced coloring are also deeply studied. The difference between the defect image and the standard template image is analyzed in detail to provide a theoretical basis for defect recognition. The system integrates the contour-based template matching technology, gray level histogram analysis and graph subtraction technology to further construct a comprehensive defect detection system, in which the change of gray level histogram is used to identify the defects related to the induced coloring power. This strategy not only effectively improves the sensitivity of detection, but also provides an efficient and reliable solution for the quality control of laser-induced coloring.

Geng [15] 's research work has injected new vitality into the thermal effect analysis in the field of laser-induced colouring. Using MATLAB platform, Geng has conducted a complete numerical simulation of the heat treatment process of 304 stainless steel plate after nanosecond laser is applied, and then deduced the approximate calculation formula of laser energy Q absorbed by the substrate surface (formula 3). The mathematical model not only deepens the understanding of the mechanism

of laser-material interaction, but also provides a powerful quantitative tool for predicting and controlling thermal effects in laser-induced coloring processes. Based on this, Geng further uses statistical principles to design a mean variance evaluation method to quantify the color stability of cells in laser-induced coloring barcodes (Formula 4). Fig. 12 color stability of each colorized cell in direct laser color marking of barcodes. It is found that when the cell edge width is zero, the cells show very high color consistency with stability indices of 92, 86 and 90, respectively. The validity and accuracy of the model are effectively verified. In addition, the mean square error of the model is only 0.67, and the goodness of fit reaches 0.88. These excellent indicators further consolidate the reliability and practicability of the model, and lay a solid theoretical foundation for the fine management of laser-induced coloring technology. At the same time, Zheng Hongyu et al. [30] introduced artificial neural network (ANN) data processing tools into the field of laser-induced coloring (LCM) and successfully constructed two high-performance models, both of which employed a double-hidden layer neural network architecture, as depicted in Fig. 9 and Fig. 10. Model one utilizes scan speed and pulse number as input variables to output RGB color values, accurately predicting the color performance of laser-induced coloring under varying process parameters, as illustrated in Fig. 11.a and Fig. 11.c. On the contrary, Model two primarily takes RGB color values as input and provides the optimal scanning speed and line spacing as output. The goal is to achieve accurate reproduction of specific color effects by adjusting these parameters (Fig. 11.b and Fig. 11.d). The results indicate that both the root mean square error (RMSE) and phase relation number (R) of the two models fall within the ideal range, thereby demonstrating the significant potential of the ANN model in enhancing the color consistency and repeatability of laser-induced coloring. Notably, Model two has been successfully implemented in the practical application of laser labeling for RGB images, as shown in Fig. 13. By measuring the digital RGB value of the image and using it as the model input, the scanning speed and line spacing required to achieve the desired image effect can be accurately estimated, which shows the practical value and broad prospect of ANN model in laser induced coloring technology. As the color stability assessment model and ANN quantitative matching method continue to evolve, laser-induced coloring technology will enable more precise color regulation and broader application scenarios. The deep integration of this technology with machine learning, artificial intelligence and other cutting-edge technologies will accelerate the transformation of the manufacturing industry to a higher level of automation and intelligence.

$$Q(x, y, z) = Q_0(-R_c) \frac{A}{\pi\sigma_x\sigma_y} e^{-\left[\frac{(x-x_0)^2}{2\sigma_x^2} + \frac{(y-y_0)^2}{2\sigma_y^2} \right]} e^{-AeZ} \quad (3)$$

In formula 1, Q_0 is the total output energy of the laser, R_c is the reflectivity, σ_x and σ_y are the standard deviation of the laser pulse centered on (x_0, y_0) , the initial ambient temperature T_0 is 283.15k, and the air convection coefficient h is 16.3w.

$$VMD(A, B) = \frac{1}{n} \sum_{i=0}^{n-1} |A[i] - B[i]| \quad (4)$$

In formula 2, A and B are sequences composed of cell color stability, and element n is 51.

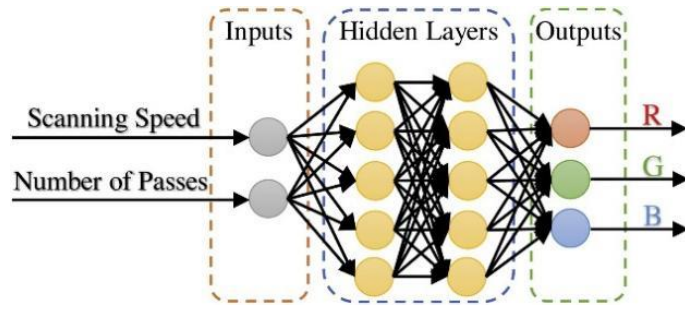


Figure 9. Configuration Model one [30]

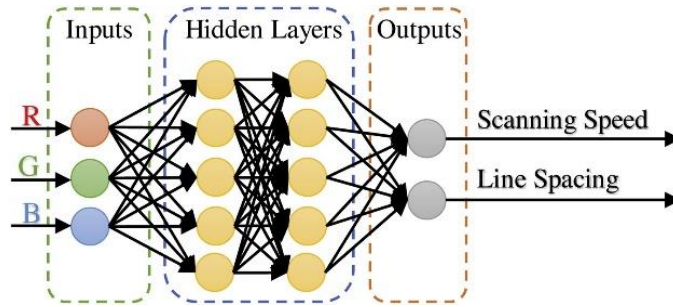


Figure 10. Configuration of Model tow [30]

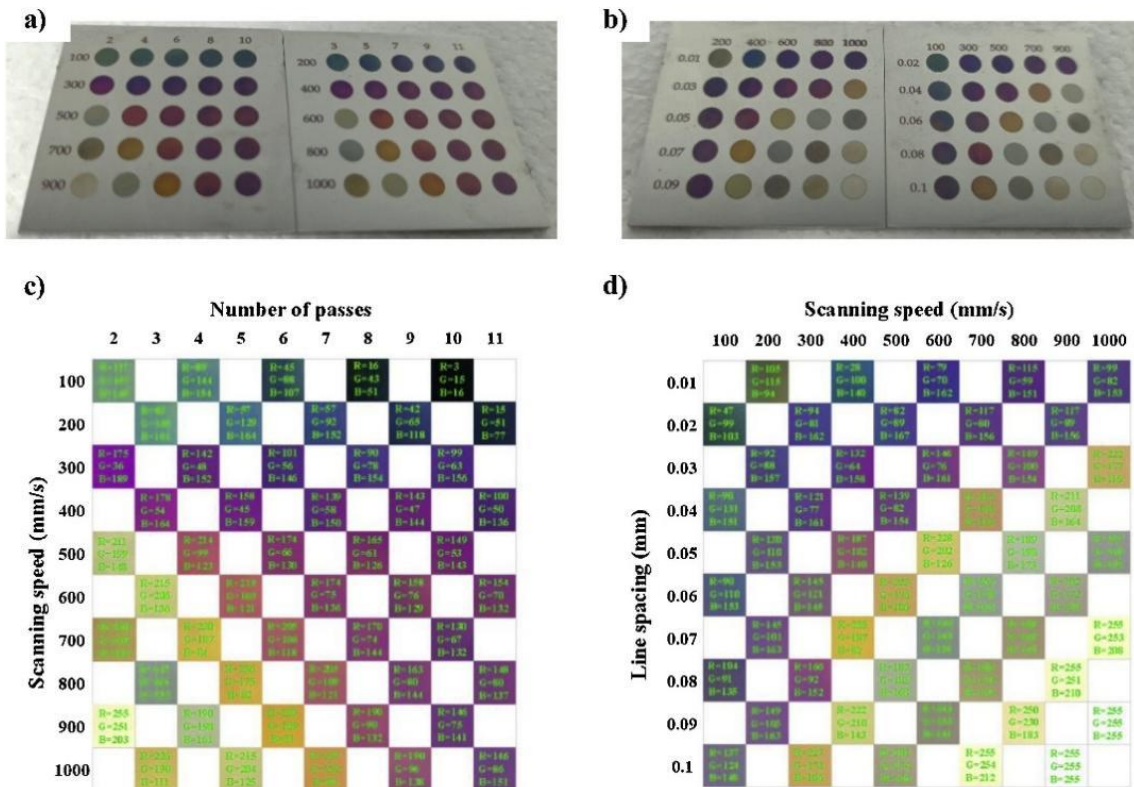


Figure 11. The experimental samples and the captured colors by optical microscope for training and testing a&c) Mode one(different scanning speed and number of passes), and b&d) Model tow (different scanning speed and line spacing) [30]

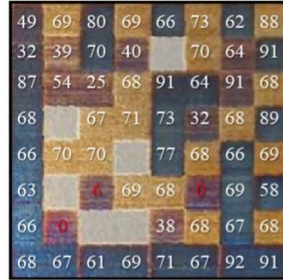
A nanosecond laser

Material: Ti6Al4V

Barcode parameter:

cell area = 4 mm²

barcode size = 8 × 8

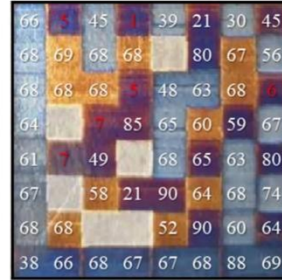


(a)

Laser parameter:

$P = 3.2 \text{ W}; l = 0.015 \text{ mm}; f = 10 \text{ kHz};$

$v = 110\text{-blue, } 130\text{-purple, } 150\text{-yellow mm/s}$



(b)



(c)

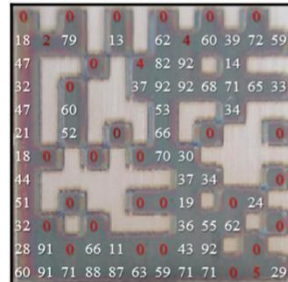
A nanosecond laser

Material: SS 304

Barcode parameter:

cell area = 0.25 mm²

barcode size = 12 × 12

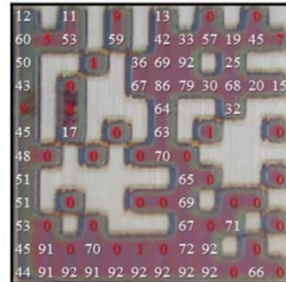


(d)

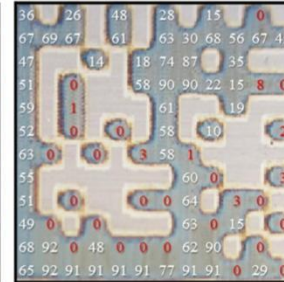
Laser parameter:

$P = 2.5 \text{ W}; l = 0.01 \text{ mm}; f = 4.14 \text{ kHz};$

$v = 90 \text{ (d), } 120 \text{ (e), } 180 \text{ (f) mm/s}$



(e)



(f)

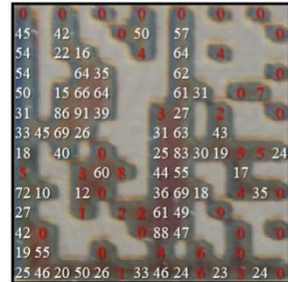
A nanosecond laser

Material: SS 304

Barcode parameter:

cell area = 0.25 mm²

barcode size = 14 × 14

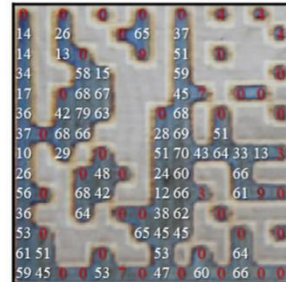


(g)

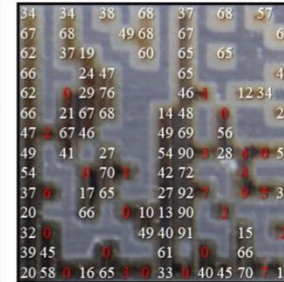
Laser parameter:

$P = 2.5 \text{ W}; l = 0.01 \text{ mm}; f = 4.14 \text{ kHz};$

$v = 140 \text{ (g), } 210 \text{ (h), } 270 \text{ (i) mm/s}$



(h)



(i)

Figure 12. Color stability of each colored cell in direct laser color marking of barcodes (a) - (c). 2. Color stability of each colored cell in direct laser color marking of barcodes (d) - (f). 3. Color stability of each colored cell in direct laser color marking of barcodes (g) - (i) [15]

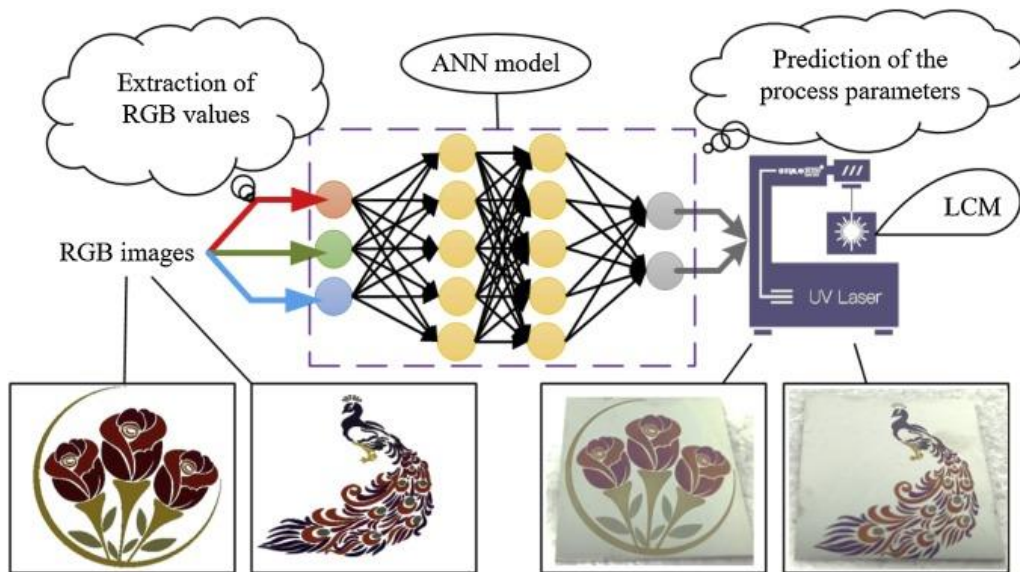


Figure 13. Artworks marked on the surface of stainless steel using Model tow [30]

6. SUMMARY AND FUTURE OUTLOOK

Laser-induced metal surface coloring technology, an efficient, environmentally friendly, and personalized innovative process, is profoundly reshaping traditional metal surface treatment methods. Its core advantage lies in precisely regulating the interaction between laser parameters and material properties to generate a diverse array of color patterns on metal surfaces. At the same time, the problem of environmental pollution caused by traditional chemical dyeing is avoided. However, to fully realize the potential of this technology, a number of complex challenges must be faced and overcome, especially the improvement of color stability and material adaptability.

In the future, the scientific research path of laser induced metal surface coloring should be clearly pointed to three key areas: First, in-depth exploration of how oxide composition and oxide film thickness affect the color generation process will serve as the pivotal factor in unraveling the enigma of color generation; Secondly, the subtle influence of different laser parameters on color performance is systematically analyzed to lay a foundation for achieving high repeatability and stability of color. Finally, the combination of laser induced coloring technology with advanced intelligent technologies such as machine vision and neural networks can not only significantly improve the level of intelligence and automation of the processing process, but also ensure the consistency and accuracy of the color.

With the deepening of research and technology iteration, the boundary of laser-induced metal surface coloring technology will continue to expand, and its application fields will also expand from industrial identification, anti-counterfeiting to artistic creation, architectural decoration and medical equipment and other dimensions, showing unprecedented market vitality and social value. Especially in the context of intelligent manufacturing, the intelligent upgrade and large-scale application of the technology will become a powerful engine to promote the transformation and upgrading of the global manufacturing industry and move towards high-quality development.

In short, the future of laser-induced metal surface coloring technology is full of infinite possibilities, which not only represents a major leap in surface treatment technology, but also a clear sign of the transition of industrial civilization to the green and intelligent era. With the tireless efforts of researchers and the positive response of industry, it is reasonable to expect that this technology will play a more significant role in promoting sustainable economic development and improving social well-being.

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