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# Quality evaluation of tourmaline red based on uniform color space

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**Abstract** Based on the uniform color space CIE 1976L*a*b*, the red colors of 310 tourmalines were conducted with the research of color colorimetry. In terms of the quantitative analysis of color indexes such as lightness, chroma and color hue, we put forward the eight-class five-level systems for quality evaluation of tourmaline red by K-Means cluster analysis. The systems were sorted from superior to inferior: Fancy Vivid, Fancy Intense, Fancy Deep, Fancy and Fancy Dark. Through Fisher discriminant, the accuracy was proved to be up to 98.7%. Furthermore, we analyzed the effects of different standard light sources ($D_{65}$, A and CWF) on tourmaline red in detail. It was pointed out that $D_{65}$ could better reflect the color of non-self-luminous object, which was suitable for quality evaluation of tourmaline red. Light source A significantly improved the chroma and hue of tourmaline red for red tourmaline display. Light source CWF reduced the chroma of tourmaline red, making the hue significantly deviated from the red. Therefore, CWF was not suitable for tourmaline red lighting. Finally, the work discussed the effects of non-color background lightness and color background on tourmaline red to derive the following results: (1) in the process of non-color background lightness transformation, the lightness and chroma of tourmaline red were sensitive and changed significantly, with high synchronism; whereas, the color hue has unobvious change. The higher lightness and chroma of tourmaline red led to larger effects of non-color background lightness transformation to visual lightness and saturation. It was thus proved that the non-color background was suitable for quality evaluation of tourmaline red. (2) In the process of color background transformation, color metal alloy background has significantly higher lightness (average lightness 83.81) and chroma (average chroma 39.21) than tourmaline red, with obvious orange hue (average hue angle 74.48). Therefore, color metal alloy background significantly enhanced the lightness and chroma of tourmaline red, thus greatly contributing to quality evaluation of tourmaline red. However, color metal alloy background made orange hue obvious, namely strengthening mixed hue of non-mainstream red, which was not conducive to quality evaluation of tourmaline red. Therefore, color metal alloy background was only suitable for inlaid jewelry material or gemstone display rather than quality evaluation.

**Keywords** Tourmaline red · Color quality evaluation · Lighting source · Background

# 1 Introduction

Tourmaline (gem tourmaline) is a colored gemstone, of which the color is the most important factor to affect quality evaluation. The color quality directly affects the value of tourmaline. The most valuable tourmaline is red tourmaline, where the purple and rose reds are the best. Red tourmaline is also called rubellite and known as "baby face" in China.

The color of tourmaline is mainly related to trace ions. The components affect the color through electronic structures. The color of tourmaline is relevant to the electric transition, charge transfer and color center. The transition of $Fe^{2+}$ leads to green; blue–green is relevant to charge transfer of $Fe^{2+} + Ti^{4+}$; brown–rose may be related to $Mn^{3+}$ stable color center [1,2]. The brilliant red is mainly caused by $Mn^{2+}$. There is also a small amount of $Cr^{3+}$ and $Fe^{2+}$, where the latter leads to purple hue in red tourmaline [3]. However,

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there are mainly brown, brown–red and dark red in nature, with great changes in hue. At present, scientific research mainly focuses on the performance of non-gemstone tourmaline as the mineral material [4–11]. The research on gemstone tourmaline–tourmaline focuses on the optimization of filling and irradiation. There is no systemic evaluation on the color although the effect of components to the color has made progress.

The quality evaluation and generation of gem color have the same elements including light source, gemstone and observer. Different light sources with different spectral energy distributions reach the gemstones to present different colors. The gemstones have different colors because of selective absorption, reflection and transmission of internal colored ion to visible light of the light source. For observers, the perception of visible light at specific wavelengths varies from person to person although the human eye has a sensitive resolution to visible light. For the same gemstone and observer, the selection of standard light sources is particularly critical for color evaluation. The color of non-self-luminous object changes with lighting transformation. Therefore, it is of great significance to discuss the effect of different standard light sources on the evaluation of tourmaline color by colorimetry theory.

According to the requirements of GB/T 20146-2006 to standard lighting source, the metamerism phenomenon of non-self-luminous object color, the detection and quality evaluation of gems, international scholars often adopt $D_{65}$ (average color temperature 6504 K) simulating cloudy daylight and A (average color temperature 2856 K) of typical incandescent lamp for family room or lighting store as standard light sources.

The background color has a significant effect on the appearance of foreground color. The effect of background color variation to color appearance of target object is usually analyzed by binocular matching method. In the field of view, different colors of adjacent areas mutually affect each other. This phenomenon is called simultaneous color contrast, which is a research direction of psychological physics [12]. The lower background color lightness leads to higher target color lightness for people; otherwise, the higher background color lightness causes lower target color lightness [13]. The effect of non-color background to color appearance involves lightness, hue and chroma of target color. Besides, its own lightness also affects the impact of the background lightness on its own color. However, the binocular matching method mainly depends on the subjective factors of human eye observation, lacking quantitative analysis of color changes. The target objects in above experiment are not transparent, while the color of gemstone material is usually not rich but transparent. Therefore, the background color variation affects the target object in different ways.

Previous research methods and conclusions cannot be fully applied to gemstone materials. Few researches on the background to appearance of gemstone color only focus on the effect of non-color background to target lightness, ignoring color background, target object chroma and hue angle changes.

With good uniformity, color space CIE 1976L*a*b* is suitable for the representation and calculation of all object colors. Therefore, it is widely adopted by all countries in the world, and taken as an international color measuring system. Nowadays, colorimetric systems are more and more widely used in gemmological research [14–17]. CIE colorimetry theory is applied in quantitative description of gemstone color. The visual characteristics of color is quantified to explore the changes of foreground color under different backgrounds, the effects of different light sources, non-color and color backgrounds to the tourmaline red.

## 2 Samples and experiments

The 310 samples are polished red hue flat arc tourmaline rings, without inclusions under the table by naked eyes. The sizes range from 4 mm × 10 mm × 10 mm to 10 mm × 18 mm × 25 mm. These samples have uniform colors under the naked eye, continuously changing lightness and saturations, covering the range of purple, red and pink.

Color i5 colorimeter was used to collect the reflected signals from the surfaces of samples by integrating sphere. Test conditions were described as follows: not including mirror reflection (SCE mode); $D_{65}$ is the reference light source; A the test light source; the measurement range 360–750 nm; the measurement time <2.5 s; the wavelength interval 10 nm; the voltage 240 V; the current 50 Hz.

Uniform color space CIE 1976L*a*b* was used as the color system of quantitative representation and analysis; Munsell color system as the contrast system.

## 3 Result discussion

### 3.1 Quality evaluation of tourmaline red

Under the standard $D_{65}$ light source, 310 samples were measured to obtain: lightness $L^* \in (16.23, 72.36)$; colorimetry index $a^* \in (2.05, 36.99)$; $b^* \in (-12.75, 11.88)$; chroma $C^* \in (2.18, 37.14)$; hue angle $h_0 \in (315.10, 34.38)$. These indexes were consistent with the color appearance of red tourmaline (see Fig. 1).

In uniform color space CIE 1976L*a*b* under standard light source $D_{65}$, the tourmaline red was quantitatively divided to derive color classification model according to the lightness (L*), chroma (C*) and hue ($h_0$).
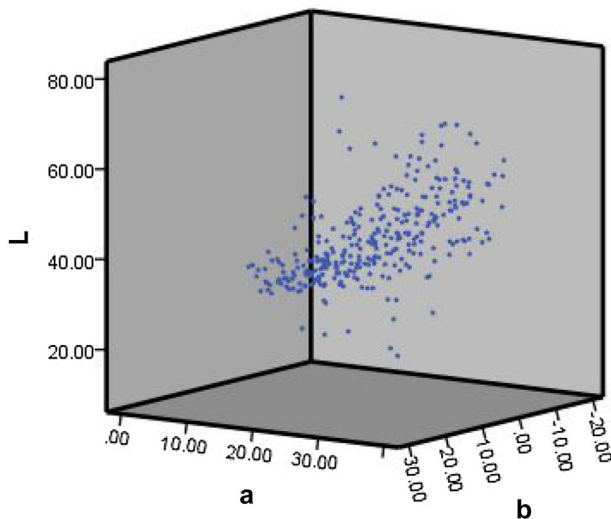
**Fig. 1** 310 Tourmaline red plots in the uniform color space CIE 1976$L^*a^*b^*$

### 3.1.1 Quality classification of tourmaline red hue

Among 17 standard colors recommended by CIE1995, 16 standard colors are formed by dividing the circle around lightness axis into 16 equal parts except for the grey. However, there are large differences between the lightness of 16 standard colors. The standard colors with highest lightness are yellow and high chroma yellow $L^* = 87$; the standard color with lowest lightness is high chroma blue $L^* = 34$.

In the three-dimensional hue coordinates based on uniform color space CIE 1976 $L^*a^*b^*$, the red (44, 37, 23) and the high chroma red (44, 58, 36) are recommended by 17 standard color center to derive the following results. The hue angle of red gamut center $h_0 = 31.80$. For standard red, the hue angle $h_0 \in (10, 32.5)$; for the pink, $h_0 \in (-12.5, 10)$; for the purple red, $h_0 \in (-35, -12.5)$; for the purple, $h_0 \in (-57.5, -35)$.

Based on uniform color space CIE 1976$L^*a^*b^*$, we measured the overall hue angle range $h_0 \in (-44.90, 34.38)$ of red colors in 310 tourmalines, indicating that the basic hue of 310 samples was red. There were 68, 226, 15 and 1 tourmalines for the red, purple red, pink and purple. This accorded with the naked eye observation results (see Table 1).

For quality evaluation of tourmaline red, the red hue was positioned as the optimum quality Level I. According to the degree of deviation from the red hue, the color levels were reduced to pink Level II, purple red Level III and purple Level IV.

### 3.2 Quality classification of tourmaline red chroma

The red chroma $C^* \in (2.18, 37.14)$ of 310 tourmalines is significantly lower than that ($C^* = 43.57$) of 17 standard colors recommended by CIE. Sample chroma concentration area ($C^* \in (10, 25)$) only belongs to the range of low saturation, which is obviously lower than the chroma distribution interval $C^* \in (14, 31)$ of ruby [18].

The chroma of the tourmaline red is divided into: $I_{gorgeous}C^* > 28$; $II_{dense}20 < C^* \leq 28$; $III_{medium}12 < C^* \leq 20$; $IV_{fresh}C^* \leq 12$.

The tourmaline red with higher chroma is often with pink and purple hues, reflecting slightly different chroma values in tourmaline reds with different hues. The saturations values of red, pink and purple red tourmalines are concentrated in $C^* \in (8, 28)$, $C^* \in (12, 31)$ and $C^* \in (20, 33)$ (see Table 1).

### 3.3 Quality classification of tourmaline red lightness

For 310 tourmalines, the red lightness values ($L^* \in (16.23, 72.36)$) are mainly in the range of $L^* \in (30, 53)$, belonging to moderate lightness.

According to the gray scale G of Gem Dialogue color card, the lightness values of 310 red tourmaline samples after hue and chroma classification are divided into brighter (V1, $G \leq 59$), bright (V2, $59 < G \leq 68$), moderate (V3, $68 < G \leq 76$), dark (V4, $76 < G \leq 82$) and darker (V5, $G > 82$). The five levels correspond to 21, 58, 85, 90 and 56 tourmalines, respectively (see Table 1).

In uniform color space CIE 1976$L^*a^*b^*$, the red and high chroma red prescribed by CIE have the lightness values of 44. The lightness value $L^* = 44$ when tourmaline red has the best chroma $C^* = 43.57$ and $C^* = 68.26$. Tourmaline red is the only standard color which is higher than the blue, high chroma blue $L^* = 36$ and the purple $L^* = 36$ in 16 standard colors specified by CIE. Therefore, the lightness of tourmaline red cannot achieve the levels of other gemstones with different colors, such as the jade green and citrine yellow. The best lightness of tourmaline red is only moderate.

Experiments show that the tourmaline red with highest lightness level is mainly concentrated in the pink and purple red tourmaline. Most red tourmalines have moderate lightness $L^* \in (40, 58)$, which also explains the phenomenon that peach and double peach with pink and purple hues have more beautiful appearances in tourmalines.

### 3.3.1 Quality classification of tourmaline red

*3.3.1.1 Cluster analysis and classification* Taking chroma coordinates $L^*$, $a^*$ and $b^*$ of red tourmaline as independent variables, we analyzed 310 tourmalines by hierarchical clustering method. After five iterations, the red tourmaline was completely unified. And then the K-Means clustering method was used to classify the tourmaline red into eight types. The color sample of each center was extracted to conduct one-way ANOVA.

**Table 1** $L^*$, $C^*$, $h_0$ of 310 tourmaline red

| $L^*$ | | $C^*$ | | $h_0$ | |
|---|---|---|---|---|---|
| III Brilliant | $L^* \geq 58$ $G \leq 59$ | I Vivid | $C^* > 28$ | I Red | $h_0 \in (10, 32.5)$ |
| | 1r+17pir+3pur | | 8r+56pir+7pur | | 68r |
| II Light | $49 \leq L^* < 58$ $59 < G \leq 68$ | II Intense | $20 < C^* \leq 28$ | II Pink red | $h_0 \in (-12.5, 10)$ |
| | 15r+42pir+1pur | | 16r+68pir+5pur | | 226pr |
| I Medium | $40 \leq L^* < 49$ $68 < G \leq 76$ | III Fancy | $12 < C^* \leq 20$ | III Purple red | $h_0 \in (-35, -12.5)$ |
| | 15r+64pir 5pur+1pu | | 20r+72pir 1pur+1pu | | 15pur |
| II Deep | $33 \leq L^* < 40$ $76 < G \leq 81$ | IV Light | $C^* \leq 12$ | IV Purple | $h_0 \in (-57.5, -35)$ |
| | 18r+67pir+5pur | | 24r+30pir+2pur | | 1p |
| III Dark | $L^* < 33$ $G > 81$ | | | | |
| | 19r+36pir+1pur | | | | |

(1) Lightness, shown by colorless grey on color simulation, is the color parameter that is independent of chroma and hue

(2) Lightness simulated color, derived from the median of Munsell neutral value scale main levels, is as follows: $L_I^* = 65$, $L_{II}^* = 55$, $L_{III}^* = 45$, $L_{IV}^* = 35$, $L_V^* = 25$

(3) Tourmaline red, pink, purple red, purple are abbreviated as r, pir, pur, p, respectively

The results show that associated probability P values of the corresponding F statistical quantities between the classes are less than highly significant level for $L^*$, $a^*$ and $b^*$ values (i.e., $P_{L^*} < 0.01$, $P_{a^*} < 0.01$ and $P_{b^*} < 0.01$). Therefore, there are significant differences among $L^*$, $a^*$ and $b^*$ values of eight types of tourmaline red. It is reasonable to divide 310 tourmaline reds into 8 types by K-Means clustering method.

Thus, we established five-level grading system of tourmaline red combined with lightness and chroma (see Table 2).

The lightness and chroma values of best tourmaline red with different hues are slightly different. For example, pink and purple red have higher lightness and chroma values than red, despite of significant deviation from standard red hue. According to the five color center division in five-level grading system, we reduced quality evaluation levels of pink, purple red and purple hues with increasing deviation degrees from red hue, thus merging F and P levels of purple red and purple as well as EX and G levels of purple. Table 3 shows the tourmaline red grading system with unified lightness, chroma and hue.

*3.3.1.2 Fisher discriminant test* Despite of wide representativeness, 310 tourmaline reds still cannot cover all the tourmaline reds. Therefore, discriminant analysis was used to speculate color classification of unknown samples based on the existing data. In the case of definite classification, we established one or more discriminant functions. After that, the undetermined coefficients in discriminant functions were determined by mass data of research object to calculate the discriminant index, thus determining the unknown sample classification.

The three-dimensional coordinates of uniform color space CIE 1976$L^*a^*b^*$ were analyzed by Fisher discriminant to simulate linear discriminant functions of five types of red tourmalines. The $L^*$, $a^*$ and $b^*$ values of the samples to be classified were substituted in the following Fisher discriminant functions to classify tourmaline red with unknown

**Table 2** Five-level grading system based on L* and C* of tourmaline red

| | | L* ≥ 58 | | 49 ≤ L* < 58 | | 40 ≤ L* < 49 | | 33 ≤ L* < 40 | | L* < 33 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| C* > 28 | G |  | EX |  | EX |  | EX |  | G |  | |
| 20 < C* ≤ 28 | F |  | G |  | EX |  | G |  | F |  | |
| 12 < C* ≤ 20 | P |  | F |  | G |  | F |  | P |  | |
| C* ≤ 12 | P |  | P |  | F |  | P |  | P |  | |

(1) The hue of simulated color is CIE standard red hue angle $h_0 = 31.80$

(2) The lightness of simulated color is the median of each lightness interval range: $L_I^* = 65$, $L_{II}^* = 55$, $L_{III}^* = 45$, $L_{IV}^* = 35$, $L_V^* = 25$

(3) The chroma of simulated color is the median of each chroma interval range: $C_I^* = 32$, $C_{II}^* = 24$, $C_{III}^* = 16$, $C_{IV}^* = 8$

**Table 3** Color grading system based on L*, C* and $h_0$ of tourmaline red

| | $L^*$ | $a^*$ | $b^*$ | Simulated color | Red | Pink | Purple red | Purple |
|---|---|---|---|---|---|---|---|---|
| I Fancy Vivid | $L^* = 43.29$ | $a^* = 27.47$ | $b^* = -1.75$ |  | EX | - | - | - |
| II Fancy Intense | $L^* = 53.58$ | $a^* = 27.35$ | $b^* = 1.12$ |  | G | EX | - | - |
| III Fancy Deep | $L^* = 41.07$ | $a^* = 19.20$ | $b^* = 1.86$ |  | F | G | EX | - |
| IV Fancy | $L^* = 63.44$ | $a^* = 24.82$ | $b^* = -2.47$ |  | P | F | G | EX, G |
| V Fancy Dark | $L^* = 32.23$ | $a^* = 11.87$ | $b^* = 0.61$ |  | - | P | F, P | F, P |

**Table 4** Fisher linear discriminant function and coefficient

| Fisher linear discriminant functions | L* | a* | b* | Constant |
|---|---|---|---|---|
| $F_1 = 3.27L^* + 1.91a^* - 0.13b^* - 98.60$ | 3.27 | 1.91 | −0.13 | −98.60 |
| $F_2 = 4.00L^* + 2.18a^* + 0.08b^* - 141.80$ | 4.00 | 2.18 | 0.08 | −141.80 |
| $F_3 = 3.04L^* + 1.43a^* + 0.10b^* - 77.73$ | 3.04 | 1.43 | 0.10 | −77.73 |
| $F_4 = 4.70L^* + 1.84a^* - 0.38b^* - 174.11$ | 4.70 | 1.84 | −0.38 | −174.11 |
| $F_5 = 2.37L^* + 0.91a^* - 0.04b^* - 45.25$ | 2.37 | 0.91 | −0.04 | −45.25 |

levels. The type with the largest function value was used as the sample category (see Table 4).

Each observed quantity was conducted with back substitution by the above five functions. Compared with original classification results, it was hoped to verify classification accuracy of tourmaline red.

Table 5 shows the accuracy of classification results of 310 known samples by discriminant analysis. The diagonal indi-

**Table 5** Accuracy of Fisher linear discriminant

| | 1 | 2 | 3 | 4 | 5 | Total |
|---|---|---|---|---|---|---|
| 1 | **94.0** | *4.0* | *2.0* | 0.0 | 0.0 | 100.0 |
| 2 | 0.0 | **98.3** | 0.0 | 0.0 | *1.7* | 100.0 |
| 3 | 0.0 | 0.0 | **100.0** | 0. 0 | 0.0 | 100.0 |
| 4 | 0.0 | *11.8* | 0.0 | **88.2** | 0.0 | 100.0 |
| 5 | 0.0 | 0.0 | 0.0 | 0.0 | **100.0** | 100.0 |

cates the ratio of correct prediction; the rest the rate of error prediction. Among 310 groups of data, 4 are misjudged, with the correct rate of 98.7%. This indicates that the linear discriminant function model can be used for the actual measurement. The category of tourmaline red is determined for grading.

### 3.4 Influence of $D_{65}$, A and CWF to tourmaline red

Thirty-nine red, pink, purple red tourmalines were tested to analyze the effect of standard light to tourmaline red.

#### 3.4.1 Influence of light source and sample to the color appearance of tourmaline

According to the requirements of GB/T 20146-2006 *CIE Standard Illuminator for Colorimetry* to standard lighting conditions, the uniformity of lighting source, the detection and quality evaluation of gems, we adopted $D_{65}$ light source (relevant color temperature 6504 K) simulating cloudy daylight and A light source (relevant color temperature 2856 K) of typical incandescent lamp for family room or store lighting, referring to the CWF light source (relevant color temperature 4150 K) for business and office in the US. Thereinto, the average daylight $D_{65}$ is the standard light source for international color quality evaluation. With relatively high energy distribution in long wave area, A belongs to colored light source close to yellow hue. However, A has high color rendering index. Therefore, the non-self-luminous object color under A light source is closer to the color under daylight. Different from first two standard light sources, CWF light source has discontinuous spectral power distribution to release a small amount of fluorescence. Although the most common in life, CWF can only be used as a reference light source for quality evaluation of tourmaline, which is almost unaffected by fluorescence [19–21].

Based on uniform color space CIE 1976L\*a\*b\*, we measured the color space coordinate, a\* and b\* of each tourmaline under $D_{65}$ light source to then calculate the chroma C\* and hue angle $h_0$. After simulation in ColoriControl, we obtained color parameters of tourmaline red under A and CWF light sources.

Different light sources have different spectral power distributions, which determine the color rendering by affecting the color rendering index of the light source. The light source will have high rendering index if the spectral power distribution curve is smooth based on close spectral radiant intensities.

The spectral power distributions of $D_{65}$ and A light source were measured and calculated to compare with theoretical value of spectral power distribution of CWF light source. It is found that the spectral power curve of $D_{65}$ light source is evenly distributed in green, yellow and red areas. The highest peak appears in blue–green area around 480 nm. With low color rendering index (Ra = 80.02) and devious spectral power distribution curve, $D_{65}$ is not suitable for illumination of tourmaline red. For CWF light source, the spectral power distribution curve appears sharp peaks at 440 and 540–580 nm. As peak and valley vary greatly, the CWF is not suitable for illumination of single crystal tourmaline. The color appearance is very sensitive to the lighting conditions of different light sources. The spectral power distribution of A light source is approximately a slanting straight line. In the visible range, red area has the strongest spectral radiation, with color rendering index up to 92.39. Because of the input of orange–red background color, A light source is suitable for illumination of tourmaline red (see Fig. 2).

Computer color simulation also demonstrates that the tourmaline under A light source has the highest lightness

**Fig. 2** Spectral power distribution of standard illuminant $D_{65}$ and A. *Note* experiment instrument PR715 SpectraScan, the measurement spectral range 360–750 nm, the wavelength interval 4 nm, the photometric accuracy ±4%, the aperture /2°, the attachment MS-55, the radiation mode radiation
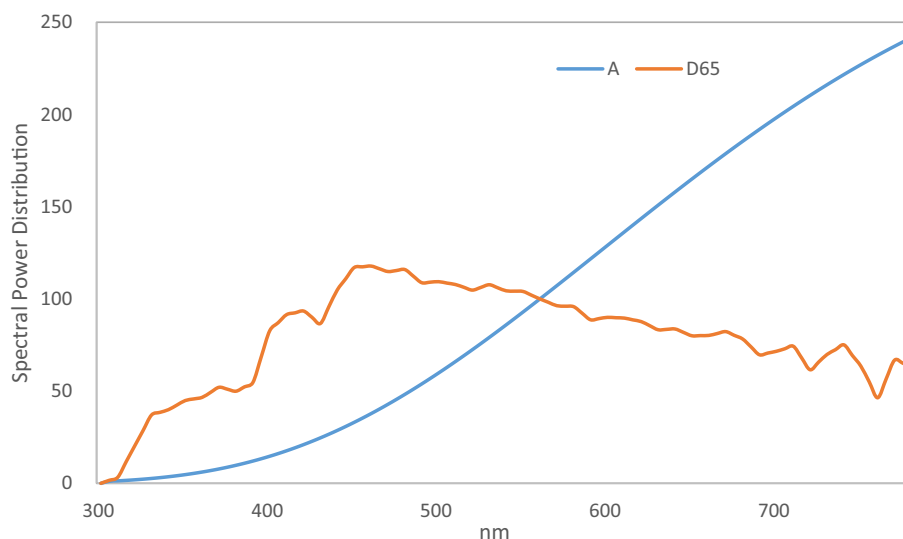
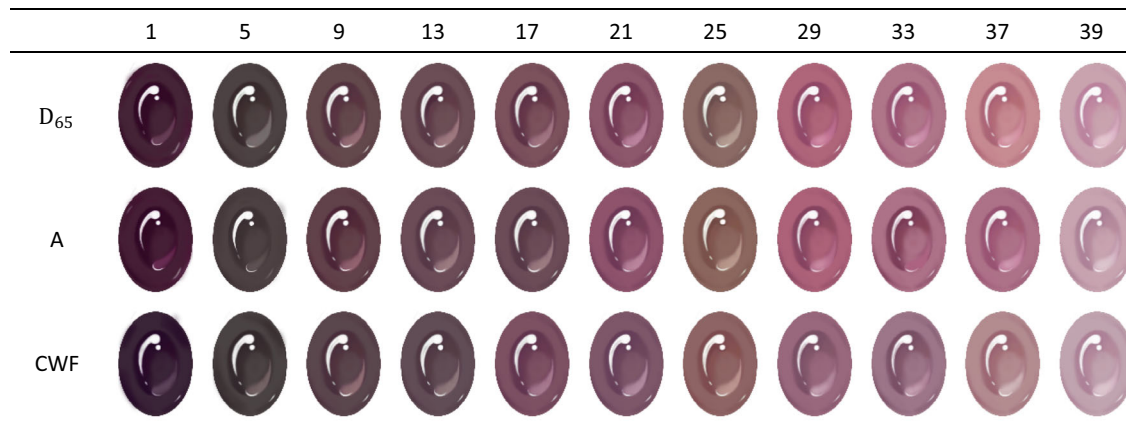**Table 6** Computer simulation of tourmaline color red under three standard light sources



**Table 7** Variance analysis of different standard light source and tourmaline red

|         |   | $L^*$   | $C^*$  | $h_0$  |
|---------|---|---------|--------|--------|
| Sample  | P | 0.00    | 0.00   | 0.00   |
|         | F | 1330.86 | 31.30  | 19.52  |
| Light source | P | 0.00 | 0.00 | 0.00  |
|         | F | 247.47  | 95.66  | 63.69  |

Significance level 0.05, extremely significance level 0.01

F is the ratio of Mean squares between groups to Mean squares within group

**Table 8** Homogeneity test on color red of tourmaline

|   | $L^*$ | $C^*$ | $h_0$ |
|---|-------|-------|-------|
| P | 0.892 | 0.168 | 0.035 |

and saturation, thus making the tourmaline more bright-colored. The sample under CWF is close to the red with dark yellow–green hue. The tourmaline under $D_{65}$ is closer to the tourmaline red under the daylight (see Table 6).

The light source and sample are independent factors to determine the appearance of the tourmaline. Non-repeated two-way ANOVA is conducted by SPSS to determine the effects of light source and sample to color index (see Table 7).

The results of two-way ANOVA show that $P \ll 0.01$, reaching extremely significant level. Therefore, the light source and sample have significant impact on jade lightness $L^*$, chroma $C^*$ and hue angle $h_0$. In ANOVA, F value can also be used to determine the significance of difference. If $F \geq P$, then there will be extremely significant (or significant) difference. In the table, $F \gg P$. It is proved that both the sample and light source have great impact on all color indices.

The influence of light source transformation on sample color is discussed by one-way ANOVA.

Different one-way ANOVAs have different sensitivities. The variance homogeneity test for each color index is adopted in order to obtain analytical method with large discrimination. If $P > 0.05$, then the variance will be homogeneous. LSD method has highest sensitivity and most

significant effect in data analysis. If $P < 0.05$, the variance is non-homogeneous. Tamhane method is used for multiple comparative analysis of data, thus realizing more significant effect. Table 8 shows that $P_{L^*} > 0.05$. In homogeneity test, LSD method is applied to analyze the effects of different light sources to color indices. When $P_{h_0} < 0.05$, we use Tamhane method.

The results of variance analysis show that the lightness has little mean value difference $\overline{\Delta L^*_{I-J}}$. Meanwhile, $P_{D_{65}-CWF} = 0.854$ and $P_{A-CWF} = 0.323$ are larger than 0.05, indicating that light source transformation has insignificant effect on sample lightness. $P_{D_{65}-CWF} = 0.021$ and $P_{A-CWF} = 0.000$ are less than 0.05 and the mean difference, thus indicating that the light source transformation has an effect on the sample saturation. $P_{D_{65}-CWF} = 0.001$ and $P_{A-CWF} = 0.001$ are much smaller than 0.05. Therefore, the light source transformation has a significant effect on the tourmaline hue (see Table 9).

### 3.4.2 Influence of $D_{65}$, A and CWF light sources to the hue of tourmaline red

Figure 3 shows that the standard light sources with different color temperatures have no obvious effect on the lightness of tourmaline. The lightness of tourmaline under A light source is slightly larger than that under $D_{65}$ and CWF light sources. This is because the A light source has higher energy in the long wave range (see Fig. 2). A light source is close to the orange light with high lightness. Therefore, the lightness of tourmaline red under A light source significantly

**Table 9** Different light source effect on color red of tourmaline

|  | Calculation method | (I) Light source | (J)Light source | Mean value difference $\overline{\Delta L_{I-J}^*}$ | P |
|---|---|---|---|---|---|
| L* | LSD | $D_{65}$ | A | −2.508 | 0.421 |
|  |  | $D_{65}$ | CWF | 0.573 | 0.854 |
|  |  | A | $D_{65}$ | 2.508 | 0.421 |
|  |  | A | CWF | 3.081 | 0.323 |
| C* | LSD | $D_{65}$ | A | −3.443 | 0.075 |
|  |  | $D_{65}$ | CWF | 4.494 | 0.021 |
|  |  | A | $D_{65}$ | 3.443 | 0.075 |
|  |  | A | CWF | 7.937 | 0.000 |
| $h_0$ | Tamhane | $D_{65}$ | A | −7.791 | 0.001 |
|  |  | $D_{65}$ | CWF | 2.080 | 0.836 |
|  |  | A | $D_{65}$ | 7.791 | 0.001 |
|  |  | A | CWF | 9.870 | 0.001 |



**Fig. 3** Different standard light sources effect on L* of tourmaline

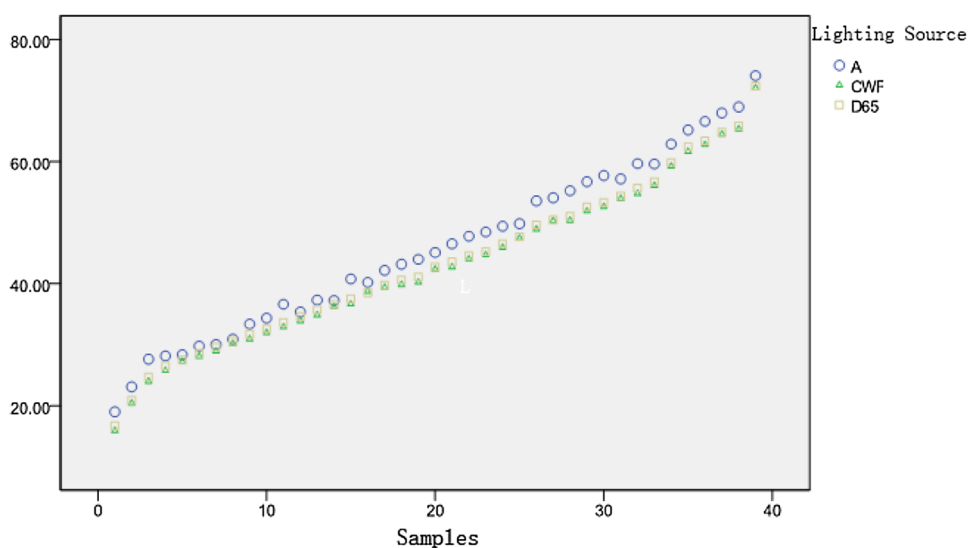increases, namely the color appearance of the sample is brighter.

### 3.4.3 Influence of $D_{65}$, A and CWF light sources to the chroma of tourmaline red

Figure 4 shows that the standard light sources have certain effect on the chroma of tourmaline. The chroma of tourmaline red successively rises under CWF, $D_{65}$ and A light sources. CWF light source has higher energy distribution within $\lambda \in (550, 620)$. Strong yellow green light reduces the chroma of tourmaline red. $D_{65}$ light source is uniformly distributed in various color lights. Therefore, the color appearance of tourmaline red under $D_{65}$ is closer to that under daylight. A light source has higher energy in long wave range. The colored light close to the orange–red hue contributes to increasing the chroma of tourmaline red and making the color appearance brighter.

The light source closest to nature is relatively objective. Therefore, the $D_{65}$ light source is suitable for quality evaluation of tourmaline. A light source is suitable for tourmaline display because of better reflecting the tourmaline red.

## 3.5 Influence of $D_{65}$, A and CWF light sources to the lightness of tourmaline red

For tourmaline purple $h_0 < -5.05$, the hue angles under A and CWF light sources are obviously larger and smaller than that under $D_{65}$ light source, respectively. For tourmaline pink $h_0 > 8.98$, the hue angles under CWF and A are insignificantly larger and smaller than that under $D_{65}$, respectively (see Fig. 5).

$D_{65}$, A and CWF light sources have different effects on tourmaline samples with different colors. CWF light source has higher energy in purple wavelength area. Under CWF

**Fig. 4** Different standard light sources effect on C* of tourmaline



**Fig. 5** Different standard light sources effect on h₀ of tourmaline
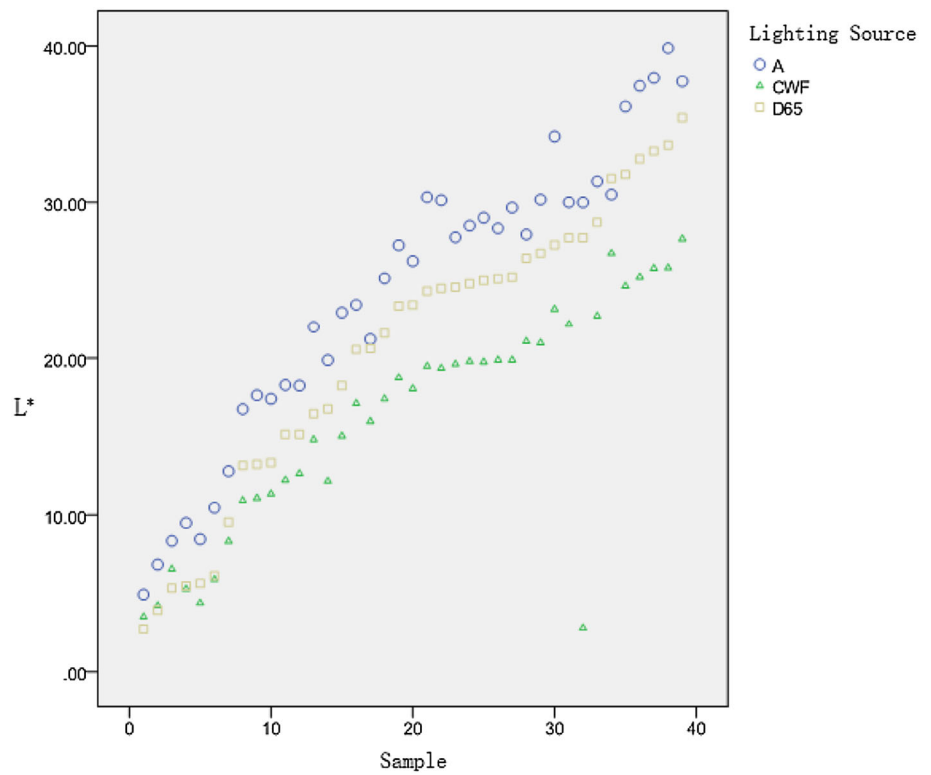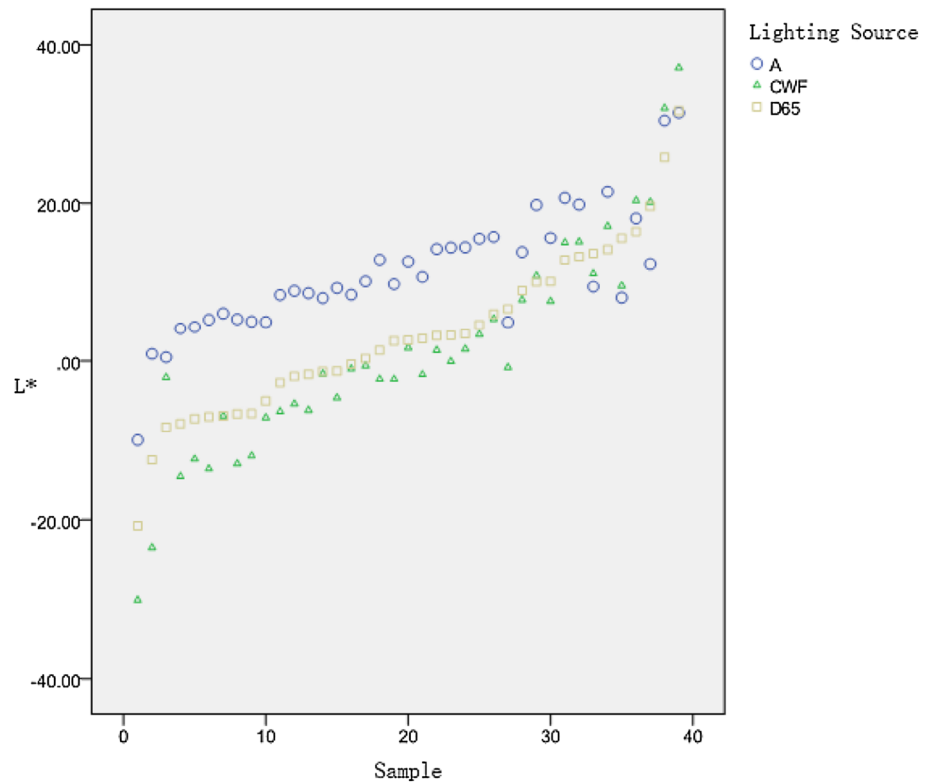


light source, tourmaline red tends to purple red, with significantly decreased hue angle. A light source adds orange red light in the purple red tourmaline sample to make the color more inclined to orange red hue. Therefore, A light source can be used for display of tourmaline samples, achieving better red. Under CWF light source, the pink tourmaline samples

can present purple. CWF is only applied in special circumstances.

The spectral power distribution and experimental result of the light source are analyzed to obtain the following conclusions.

(1) Within the 360–780 nm range, $D_{65}$ light source has more uniform energy distribution than A and CWF light sources. It also has similar relative spectral power distribution with measured daylight. Without other colors, the $D_{65}$ is the closest to natural daylight effect, thus better reflecting the true color of object. Therefore, the $D_{65}$ light source is suitable for quality evaluation of tourmaline red.

(2) The color temperature of A light source (2856 K) is lower than that of $D_{65}$ (6504 K) and CWF (4150 K) light sources. The energy in long-wave red area is significantly higher than that in short-wave blue–purple area. Light source overall shows yellowish effect to significantly improve chroma and hue of tourmaline red. Therefore, A light source is suitable for red tourmaline display.

(3) CWF light source has higher energy distribution within the wavelength $\lambda \in (550, 620)$. The preference for yellow–green light reduces the chroma of tourmaline red, thus making the hue significantly deviated from the red. Therefore, CWF light source is not suitable for illumination of tourmaline red.

## 3.6 Influence of background to tourmaline red (12 and 15 grains)

As a high-grade single crystal gem, tourmaline also has strong gloss (glass cluster), high transparency (transparent–sub-transparent) and red color with slightly higher saturation. The different colors of adjacent areas mutually affect each other in field of view. Therefore, the background transformation has an obvious impact on the color appearance. In gemmology, the research on the effects of background changes on color appearance of gemstones mostly focuses on the qualitative description by visual inspection rather than quantitative analysis. The experiments are respectively conducted under non-color and color backgrounds to explore the changes of the foreground color in different backgrounds, thus quantifying the specific visual characteristics of target object color. At last, we determine the optimal color rendering background for evaluation and display of tourmaline red by analyzing the effects of non-color and color backgrounds to color properties of tourmaline.

Non-color and color background lightness experiments were conducted by 12 well-polished purple-red, red and pink tourmalines ($1^{\#}$–$12^{\#}$) with little inclusion, medium lightness and low chroma as well as five tourmalines ($1^{\#}$–$5^{\#}$) which are suitable for inlaying precious metal into finished products.

In non-color background lightness experiments, we used nine grayscale cards (N5, N7, N6, N5, N4, N3, N2 and N1) in Munsell neutral value scale as test backgrounds. Figure 2 shows the lightness values. Table 12 shows the simulated color blocks. We also selected six pieces of high purity *Reference Materials for Jewelry gold Components* in *Reference Materials for Gold and Gold Jewelry Series Components* (corresponding to six gold alloys with different gold purities) as test background of color background lightness. The six gold alloys were made by gold, silver and copper according to different proportions (corresponding to 24K, 24K, 22K, 20K, 18K and 16K).

As a jewelry stone, tourmaline red shows a significant change against alloy metals with different gold purities, which includes not only the platinum and silver alloys of different purities with the lightness changes, but also the yellow and red K gold of different purities with the lightness, chroma and color changes. Even the non-color backgrounds with different gray scales can lead to significant difference in color appearance because of different color characteristics [22–24]. Therefore, the background can be transformed to discuss the effects of lightness, chroma and hue to color appearance of tourmaline red.

### 3.6.1 Influence of non-color background to tourmaline red

The effect of non-color background on color appearance of tourmaline red is reflected in lightness, chroma and hue to varying degrees. The lightness of gemstone also restricts the effect of background lightness.

We used grayscale card of the most popular Munsell system in the world: Munsell neutral value scale. The chroma was not displayed in the color card, but the lightness was divided into 37 levels from N0.5 to N9.5 with the spacing N=0.25. Therefore, the color parameters measured under Reference Background N9 were regarded as body color parameters, namely self parameters. After that, the N8, N7, N6, N5, N4, N3, N2 and N1 were successively selected as the contrast backgrounds.

We tested the color parameters of 12 samples under N9 background to simulate the color appearance. The self lightness $L^* \in (36.02, 59.42)$ belongs to medium level; the self chroma $C^* \in (11.54, 38.76)$ has large span. With narrow distribution, the self hue angles $h_0 \in (6.12, 14.99)$ are concentrated in the range which centers the red and slightly tends to purple and orange hues. This is because the samples are selected for the tourmaline red.

In the background transformation from N9 to N1, the average visual lightness $\overline{L^*}$ of 12 tourmaline reds overall decreases with the decrease of background lightness, and reaches the minimum $\overline{L_{N3}^*} = 29.12$ until the background is N3. When the background lightness further decreases, the average visual lightness gradually rises to the level close to

**Fig. 6** The relationship of tourmaline $\overline{L^*}$, $\overline{C^*}$, $\overline{h_0}$ from the change of Munsell neutral value scale *N1–N9*



| Munsell Neutral Value Scale: N9-N1 | N1 Y=1.21 L*=10.63 | N2 Y=3.13 L*=20.56 | N3 Y=6.55 L*=30.76 | N4 Y=12.00 L*=41.22 | N5 Y=19.77 L*=51.58 | N6 Y=30.05 L*=61.70 | N7 Y=43.06 L*=71.60 | N8 Y=59.10 L*=81.35 | N9 Y=78.66 L*=91.08 |
|---|---|---|---|---|---|---|---|---|---|
| Ave.L* | 32.23 | 29.57 | 29.12 | 32.00 | 32.27 | 35.82 | 38.27 | 44.66 | 48.66 |
| Ave.C* | 18.72 | 16.18 | 17.00 | 14.20 | 17.00 | 18.82 | 25.52 | 26.74 | 28.84 |
| Ave.h0 | 11.05 | 11.01 | 10.97 | 8.68 | 9.43 | 9.51 | 10.21 | 11.22 | 11.62 |
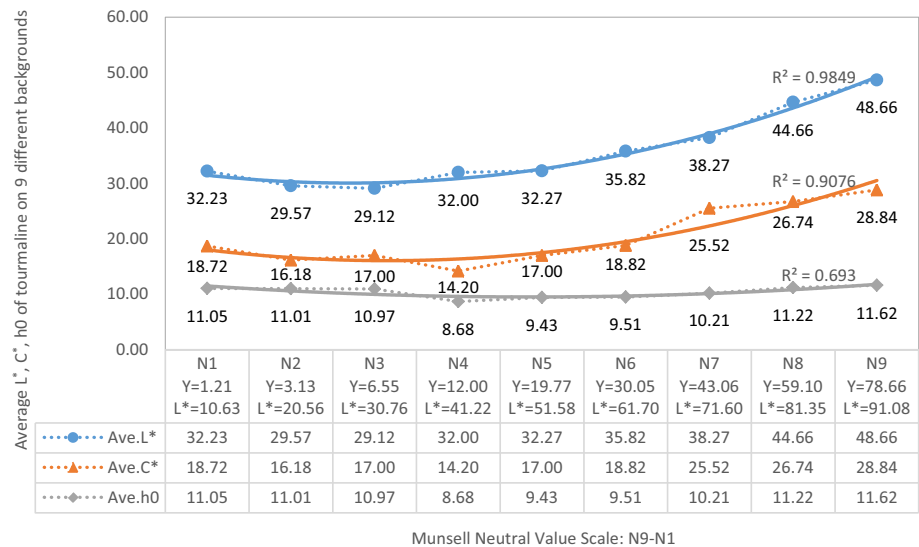
N4; the average visual chroma shows similar trend, but with unobvious regulation; the average visual hue angle almost has no regulation (see Fig. 6).

One-way ANOVA is used to analyze the effects of background lightness change to the lightness L*, the chroma C* and the hue angle $h_0$ of the tourmaline red.

The sensitivity of one-way ANOVA is improved to obtain the method of large discrimination. Firstly, the variance homogeneity test is conducted according to different color indexes. If the significance is greater than 0.05, then the variance is homogeneous. With highest sensitivity and most significant effect of data analysis, LSD method is suitable for multiple comparisons of specific groups which have been determined to be implemented in advance. If the significance is less than 0.05, then the variance is inhomogeneous. As pairwise comparison based on t test principle, Tamhane method can be used for multiple comparative analysis, achieving more significant effect.

Homogeneity test results show that the significance $P_{a^*} > 0.05$, $P_{b'^*} > 0.05$, $P_{C^*} > 0.05$ and $P_{h_0} > 0.05$. The LSD method is used to analyze the effects of different light sources on them through homogeneity test. When $P_{L^*} < 0.05$, Tamhane method will be used to analyze the effects of different backgrounds.

The results of one-way ANOVA show that non-color background lightness variation has significant effects on lightness and chroma of tourmaline red, with smallest effect on the hue ($P_{h_0} > 0.05$) (see Table 10).

*3.6.1.1 Visual lightness changes of samples* In the background transformation from N9 to N1, the maximum difference between the average lightness values of 12 samples $\overline{\Delta L^*} = 19.54$, which proves that the decrease of background lightness significantly reduces the visual lightness of sample, with the correlation coefficient r=0.886. When

the background is N9–N6, the visual lightness of tourmaline red greatly decreases. When the background ranges from N6 to N3, tourmaline red has a slower descent velocity of visual lightness. When the background lightness is as low as N3 (namely $L^*_{N3} = 30.76$), the average visual lightness of tourmaline red reaches the minimum ($\overline{L^*} = 29.12$). Meanwhile, the lightness difference under N9 and N3 backgrounds reaches the maximum ($\Delta L^* = 18.66$).

Experiments show that the visual lightness of sample significantly changes with the background lightness. Under non-color background with high lightness, the tourmaline red tends to show higher lightness, which is consistent with the color perception effect. When the tourmaline red has too high or too low lightness, the visual lightness will be hardly affected by the lightness of non-color background (see Fig. 7).
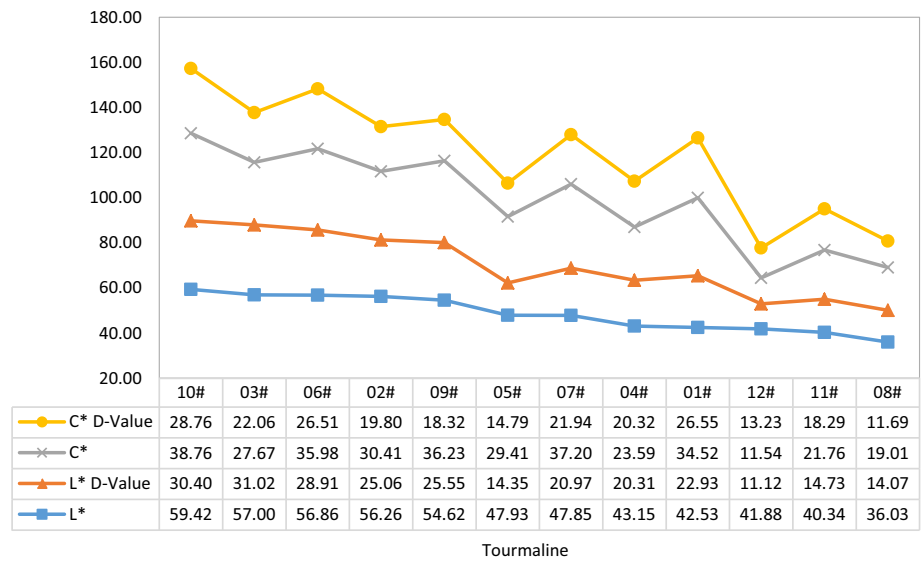
Different lightness values of tourmaline reds lead to different effects of non-color background lightness. Samples $10^\#$, $3^\#$ and $6^\#$ have high lightness values ($10^\#$ ($L^* = 59.42$, $C^* = 38.76$); $3^\#$ ($L^* = 57.00$, $C^* = 27.67$); $6^\#$ ($L^* = 56.86$, $C^* = 35.98$)). Therefore, the visual lightness variations are significantly large after non-color background lightness transformation ($\Delta L^*_{10\#} = 30.40$; $\Delta L^*_{3\#} = 31.02$; $\Delta L^*_{6\#} = 28.91$). Samples $8^\#$ and $12^\#$ have low lightness values ($8^\#$ ($L^* = 36.03$, $C^* = 19.01$); $12^\#$ ($L^* = 41.88$, $C^* = 11.54$)). Therefore, the visual lightness values have the least obvious changes after non-color background lightness transformation ($\Delta L^*_{8\#} = 14.07$; $\Delta L^*_{12\#} = 11.12$). For the tourmaline red with higher self lightness, the visual lightness is more susceptible to background lightness (see Fig. 7).

Sample and background lightness are two independent factors that do not interfere with each other. Therefore, we conduct non-repeated two-way ANOVA of lightness mean value and non-color background lightness of each sample,

**Table 10** The result of one-way ANOVA from non-color bBackground lghtness to L*, C*, h_0 of tourmaline optical red

| | | Quadratic sum | df | Mean squares | F | Significance |
|---|---|---|---|---|---|---|
| L* | Between-group | 4474.397 | 8 | 559.3 | 18.595 | 0 |
| a* | Between-group | 2535.655 | 8 | 316.957 | 7.721 | 0 |
| b* | Between-group | 142.7 | 8 | 17.837 | 6.442 | 0 |
| C* | Between-group | 2667.828 | 8 | 333.479 | 7.843 | 0 |
| h_0 | Between-group | 182.207 | 8 | 22.776 | 1.512 | 0.163 |

**Fig. 7** The change of tourmaline optical red L* and C* from the change of non-color background lightness



| | 10# | 03# | 06# | 02# | 09# | 05# | 07# | 04# | 01# | 12# | 11# | 08# |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C* D-Value | 28.76 | 22.06 | 26.51 | 19.80 | 18.32 | 14.79 | 21.94 | 20.32 | 26.55 | 13.23 | 18.29 | 11.69 |
| C* | 38.76 | 27.67 | 35.98 | 30.41 | 36.23 | 29.41 | 37.20 | 23.59 | 34.52 | 11.54 | 21.76 | 19.01 |
| L* D-Value | 30.40 | 31.02 | 28.91 | 25.06 | 25.55 | 14.35 | 20.97 | 20.31 | 22.93 | 11.12 | 14.73 | 14.07 |
| L* | 59.42 | 57.00 | 56.86 | 56.26 | 54.62 | 47.93 | 47.85 | 43.15 | 42.53 | 41.88 | 40.34 | 36.03 |

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namely 12 lightness levels of the sample and 9 lightness levels of non-color background.

Firstly, the Munsell lightness V is transformed into the lightness L* in uniform color space CIE 1976L*a*b*.

$$L^* = \left(\frac{Y}{Y_0}\right)^{\frac{1}{3}} - 16,$$

where Y is the luminance factor in Munsell color system; $Y_0 = 100$.

Figure 6 shows the results of lightness transformation.

The results of non-repeated two-way ANOVA show that Sig = 0.000 ≪ 0.005, indicating that the visual lightness of sample is significantly affected by self and background lightness of red tourmaline.

*3.6.1.2 Visual chroma changes of samples* In the background transformation from N9 to N1, the maximum difference between average chroma values of 12 samples $\Delta C^* = 14.64$, which proves that the decrease of background lightness significantly reduces visual chroma of sample, with correlation coefficient r=0.808. The significance of chroma change is slightly lower than that of lightness change, which can also be perceived by human eye; when the background ranges

from N9 to N4, the visual chroma of tourmaline red largely decreases. When the background lightness is as low as N4 ($L_{N4}^* = 41.22$), the average visual chroma of tourmaline red reaches the minimum ($\overline{C^*} = 14.20$). Meanwhile, the chroma difference under N9 and N3 backgrounds reaches the maximum ($\Delta C^* = 14.62$). When the background transforms from N4 to N1, the visual chroma of tourmaline red slightly rises. The overall trend of visual chroma is highly consistent with the visual lightness of tourmaline red affected by background (r=0.930). In the N3–N4 area, visual lightness and chroma of tourmaline red synchronously reduce to the lowest, thus indicating a higher correlation in the non-color background lightness transformation.

Experiments show that the visual lightness of sample significantly changes with the background lightness. Only under non-color background with high lightness can the tourmaline red show higher visual chroma, which is consistent with the color perception effect. It is verified that the visual chroma is not affected by the non-color background lightness when the tourmaline color is too high or too low (see Fig. 7). In addition, the quadratic polynomial of sample visual chroma fitted with the non-color background lightness has quadratic term coefficient of 0.423, which is lower than the visual lightness coefficient (0.484). Therefore, the visual chroma has lower rate of change than visual lightness, indicating that the visual

chroma is less sensitive to the change of background lightness than the visual lightness of sample.

Different chroma values of tourmaline reds lead to different effects of non-color background lightness. This is consistent with the different effects of the non-color background lightness caused by different lightness values of tourmaline red. Samples $10^\#$, $6^\#$ and $1^\#$ have high chroma values ($10^\#$ ($C^* = 38.76$, $L^* = 59.42$); $6^\#$ ($C^* = 35.98$, $L^* = 56.86$); $1^\#$ ($C^* = 35.98$, $L^* = 56.86$)). Therefore, the visual chroma variations are significantly large after non-color background lightness transformation ($\Delta C^*_{10\#} = 28.76$; $\Delta C^*_{6\#} = 26.51$; $\Delta C^*_{1\#} = 26.55$). Samples $12^\#$ and $8^\#$ have low chroma values ($12^\#$ ($L^* = 41.88$, $C^* = 11.54$); $8^\#$ ($L^* = 36.03$, $C^* = 19.01$)). Therefore, the visual chroma values have the least obvious changes after non-color background lightness transformation ($\Delta L^*_{12\#} = 13.23$; $\Delta L^*_{8\#} = 11.69$). For the tourmaline red with higher self chroma, the visual chroma is more susceptible to background lightness.

It is worth noting that the tourmaline red $10^\#$ has high lightness and chroma. Therefore, the visual lightness and chroma are most affected by non-color background lightness transformation. Tourmaline reds $8^\#$ and $12^\#$ have low lightness and chroma, so the visual lightness and chroma are least affected by the non-color background lightness transformation.

*3.6.1.3 Visual hue changes of samples* The visual hue angle of tourmaline red changes insignificantly with non-color background lightness transformation (correlation coefficient r = 0.091), which is different from visual lightness ($r_{h_0 \times L^*} = 0.412$) and chroma ($r_{h_0 \times L^*} = 0.576$).

Visual color angle changes little with the non-color background lightness (maximum difference $\Delta h_0 = 2.94$). The lightness and chroma values are unchanged. If tourmaline red hue angle increases or decreases by $1^\circ$, then the average color difference will be less than 1.5, namely 1/2 of human eye resolution limit, by color difference formula CIE2000 for accurate analysis of red subtle differences. Therefore, the changes are not easily perceived by the human eye.

It is worth noting that the tourmaline red tends to the red hue ($h_0 = 8.68$) under non-color background N4. When the non-color background lightness gradually increases ($h_0 = 11.62$) or decreases ($h_0 = 11.05$), the tourmaline red tends to orange hue. Therefore, the transformation of non-color background lightness slightly changes the visual hue of tourmaline red. It is recommended that neutral gray non-color background N4 or N5 is used for hue judgment in quality evaluation of tourmaline red.

The change of background lightness significantly affects the visual lightness $L^*$ and visual chroma $C^*$ of tourmaline red, with least effect on $h_0$.

The visual lightness change of tourmaline red is significantly correlated with the change of background lightness. As the background lightness decreases, the sample visual lightness rises after descend, with the inflection point near the N3. Tourmaline red with high self lightness is more susceptible to the impact of background lightness. For tourmaline red, the visual chroma is less sensitive to background lightness transformation than the sample lightness. When the background lightness is greater than N4, the visual chroma contrast will be proportional to the lightness ($\Delta C^* = 14.64$). The visual chroma changes under different backgrounds are relevant to self chroma. Too low background lightness value leads to low self chroma. Therefore, it is difficult to distinguish the change of visual color. The chroma value will have little change when the visual lightness corresponding to infection point changes to N1 ($\Delta C^* = 4.52$). The hue angle insignificantly changes with background lightness, which is even hardly perceived by human eyes. In the background transformation from N9 to N4, the tourmaline red shifts from orange to purple red hues. When the background changes from N4 to N1, the tourmaline red will shift from purple to orange red hues. This shows that the change of background lightness will lead to the shift of sample hue. Therefore, wrong judgment should be noticed in the evaluation of red tourmaline.

*3.6.2 Influence of color background to tourmaline red*

Tourmaline samples $1^\#$–$5^\#$ were tested under the backgrounds of six metal sheets with different formulations (*Reference Materials for Gold and Gold Jewelry Series Components* in China) (see Table 11).

*3.6.2.1 Influence of color background* Different metal sheets were used as controllable variables for one-way ANOVA. For the number of metal sheets and dependent variable $C^*$, P is statistically significant ($P < 0.005$), which indicates that different metal sheets significantly affect Samples $C^*$. For $L^*$ and $h_0$, P is statistically insignificant ($P \gg 0.05$), indicating that there is no difference between sample lightness and hue under the backgrounds of different metal sheets.

The lightness values of six color metal backgrounds have little changes ($L^* \in (79.29, 89.12)$), responding to Munsell black and white card N8–N9. The partial correlation analysis is used to explore the effect of metal sheet chroma and hue to sample visual chroma, thus eliminating the influence of metal sheet lightness. Taking metal sheet lightness as dependent variable, the sample visual chroma, metal sheet chroma and hue as independent variables, Pearson correlation analysis is used to obtain the correlation coefficients between visual chroma of tourmaline red, the metal sheet chroma and hue angle (0.440 and −0.379). The correlation coefficients pass the statistical test of significance. It is proved that the

**Table 11** Color parameters of metal background and the average five piece tourmaline red color parameters based on this background

| | K | Au% | Ag% | Cu% | L* | C* | $h_0$ | $\overline{L^*}$ | $\overline{C^*}$ | $\overline{h_0}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| GBW02751a | 24 | 99.99 | 0.00 | 0.00 | 83.78 | 47.69 | 74.33 | 43.94 | 38.10 | 27.49 |
| GBW02754a | 24 | 99.60 | 0.20 | 0.20 | 79.29 | 45.14 | 71.97 | 43.40 | 36.17 | 27.23 |
| GBW02758a | 22 | 91.68 | 4.14 | 4.14 | 83.22 | 41.41 | 72.48 | 45.54 | 36.65 | 28.45 |
| GBW02759a | 20 | 85.00 | 7.45 | 7.51 | 85.85 | 41.08 | 73.86 | 41.55 | 36.28 | 27.09 |
| GBW02761a | 18 | 74.99 | 14.95 | 10.02 | 89.12 | 35.74 | 76.67 | 44.00 | 34.98 | 28.41 |
| GBW02763a | 16 | 64.99 | 24.92 | 10.02 | 81.60 | 24.19 | 77.56 | 41.50 | 31.42 | 23.79 |

(1) L*, C*, $h_0$ are the color parameters of six metal sheets. (2) $\overline{L^*}$, $\overline{C^*}$, $\overline{h_0}$ are the color parameters of five piece tourmaline red

**Table 12** The simulation of color of sample 1# and 2# on different backgrounds



visual chroma of tourmaline red has significantly positive and negative correlations with the chroma and hue of color metal background, respectively. The change of visual chroma of tourmaline red is more affected by the chroma of metal background. This also verifies that the chroma of background color significantly affects chroma of foreground color.

Different metal compositions in the alloy lead to different color backgrounds. Ning Yuantao discussed the Au–Ag–Cu alloy based on Au. Research shows that the addition of Ag makes the alloy have a tendency to green hue, thus decreasing a*. Besides, the addition of Cu makes the alloy change to red hue, thus increasing a*.

Multivariate regression analysis of Ag and Cu are conducted to obtain the following equations. (1) Standardized regression equation: $C^* = 1.153 \times Ag + 0.190 \times Cu$ (the goodness of fit = 0.976). (2) Non-normalized coefficient regression equation: $C^* = 45.939 - 0.997 \times Ag + 0.348 \times Cu$. The contribution of independent variable to dependent variable is measured by the normalized regression coefficient. It is found that the increase of metal sheet chroma is insignificantly caused by the increase of Cu content. The decrease of metal sheet chroma is significantly caused by the decrease of Ag content.

*3.6.2.2 Comparison of influences of color and non-color backgrounds* Five samples for color background tests are also used for non-color background tests. It is found that the average visual lightness ranges of five tourmaline reds

under color alloy and non-color backgrounds are $\overline{L^*} \in$ (41.50, 45.54) and $\overline{L^*} \in$ (40.07, 46.33), respectively. Under color metal alloy backgrounds, the visual lightness of tourmaline red is very close to its own lightness ($L^* = 49.37$). Therefore, the color metal alloy can better display the lightness of tourmaline.

The average visual chroma of five tourmaline reds ($\overline{C^*} = 35.60$) is significantly higher than that under non-color background N9 ($\overline{C^*} = 35.60$), and higher than visual chroma of tourmaline under all non-color backgrounds. It is proved the background color greatly enhances the foreground color under color metal alloy background. Therefore, the color metal alloy can significantly improve the visual chroma of tourmaline, thus making the tourmaline red richer and brighter.

The average visual hue angle of five tourmaline reds ($\overline{h_0} = 27.08$) is significantly higher than that under non-color background N8 ($\overline{h_0} = 11.44$). The average offset $\overline{\Delta h_0} = 16.20$; the maximum offset $\overline{\Delta h_0} = 16.20$. Compared with tourmaline red hues under all non-color backgrounds, the red hue under color background significantly changes to orange hue. Therefore, the color metal alloy can make the red tend to orange hue to achieve easy identification of naked eyes, which is unfavorable for the quality evaluation of tourmaline red.

Table 12 shows simulated color blocks of tourmaline samples 1# and 2# under different color and non-color backgrounds.

Different color metal alloy backgrounds have significant high lightness ($\overline{L^*} = 83.81$), chroma ($\overline{C^*} = 39.21$) and obvious orange hue ($\overline{h_0} = 74.48$). Compared with the effect of non-color background to color appearance of tourmaline red, different color metal alloy backgrounds significantly enhance lightness and chroma of tourmaline red, thus greatly contributing to quality evaluation of tourmaline red. However, non-mainstream red hues such as orange are strengthened, which is obviously not conducive to quality evaluation of tourmaline red. Thus, different color metal alloy backgrounds are suitable for mosaic or display materials rather than quality evaluation.

## 4 Conclusions

For 310 tourmaline samples under standard light source $D_{65}$, the lightness $L^* \in (16.23, 72.36)$; the color indexes $a^* \in (2.05, 36.99)$, $b^* \in (-12.75, 11.88)$; the chroma $C^* \in (2.18, 37.14)$; the hue angle $h_0 \in (315.10, 34.38)$. These samples belonged to red gemstones with medium lightness and low chroma.

The tourmaline reds with highest lightness and chroma were mostly concentrated in the pink and purple, significantly deviating from the standard red color gamut. Therefore, we reduced the quality evaluation levels of pink, purple red and purple hues according to the deviation degrees from the red hue. Through K-Means cluster analysis, 310 pieces of tourmaline reds were divided into 8 categories. Combined with lightness and chroma, we established five-level classification system. According to the division of five color centers, the hue factor was added to finally form decreasing quality levels including Fancy Vivid, Fancy Intense, Fancy Deep, Fancy, Fancy Dark.

The classification result was verified by Fisher discriminant to derive correct rate of 98.7%, thus demonstrating the feasibility of the classification method.

$D_{65}$, A, and CWF light sources had different effects on different tourmaline reds. (1) With uniform spectral power distribution close to natural light, $D_{65}$ light source better reflected the color of non-self-luminous object, which was suitable for quality evaluation of tourmaline red. (2) With high energy of the orange–red area, A light source significantly improved the chroma and hue of tourmaline red, which was suitable for the display of red tourmaline. (3) With high energy of yellow–green area and heterogeneous spectral power distribution, CWF light source reduced the chroma of tourmaline red, thus making the hue significantly deviate from the red. Therefore, it was not suitable for illumination of tourmaline red.

The effect of non-color background lightness on tourmaline red was analyzed to derive the following conclusions. (1) The transformation of non-color background lightness

had significant effects on the lightness and chroma of tourmaline red, but the effect on the hue is insignificant. (2) As non-color background lightness transforms, the lightness and chroma of the tourmaline red are sensitive to the hue, with high synchronization. (3) The greater lightness and chroma of tourmaline red lead to larger effect of background lightness transformation to visual lightness and chroma. Therefore, it was proved that non-color background was suitable for quality evaluation of tourmaline red.

The effect of color background on tourmaline red showed that different color metal alloy backgrounds had significant high lightness ($\overline{L^*} = 83.81$), chroma ($\overline{C^*} = 39.21$) and obvious orange hue ($\overline{h_0} = 74.48$). Compared with the effect of non-color background to color appearance of tourmaline red, different color metal alloy backgrounds significantly enhanced lightness and chroma of tourmaline red, thus greatly contributing to quality evaluation of tourmaline red. However, non-mainstream red hues such as orange were strengthened, which was obviously not conducive to quality evaluation of tourmaline red. Thus, different color metal alloy backgrounds were suitable for mosaic or display materials rather than quality evaluation.

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