The measuring method for actual total magnification of metallographic microscope — digital image method

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Abstract. In this paper, taking MM6 metallographic microscope $160\times$ as an example, one kind of new method is studied on measuring actual total magnification of metallographic microscope by measuring digital images, the digital image is virtual image viewed through eyepiece of microscope and acquired by digital camera instead of eyes. Results show: 1) The digital images of $5/100$ ocular micrometer and $1/100$ stage micrometer in the eyepieces of microscope are acquired. The digital images of the $5$ grade gauge block, which is $5$mm length and is from camera $250$ mm, are acquired in the same acquiring conditions. The lengths of the ocular micrometer and gauge block in the digital image are measured, and then the magnification of eyepieces is calculated. The lengths of the ocular micrometer and stage micrometer in the same digital image are measured, and then the magnification of objectives and tube factor is calculated. The actual total magnification of metallographic microscope is the product of magnification of eyepieces and magnification of objectives and tube factor; 2) For $160\times$ magnification of MM6 metallographic microscope, the measurement result of actual total magnification are stated as: $154.8\times$, $U=2.8\times$, $k=2$, and the actual relative deviation is $-3.2\%$. 3) The digital image measuring method for actual total magnification of metallographic microscope can be a standardized method.

1. Introduction

Microscope is widely used in biology, medicine, mineral, metallurgy, machinery and other fields. The magnification is an important parameter for microscope; it is the first consideration factor in the microscope purchase and use. The magnification accuracy of metallographic microscope has great influence on the metallographic testing results and metallographic analysis results. For the microscope magnification, there are deep researches in the field of optics [1]. There are also different depths of research in the field of material science. For example, the scholars have studied the influence of microscopy amplifying multiple on the measurement of fracture toughness [2].

In the technical field of optical system, there are visual magnification and lateral magnification. The visual magnification is the virtual image magnification that produced by the microscope. The visual magnification is the ratio of the tangent of the angle that the object is viewed through amplifying system and the tangent of the angle that the object is viewed with the naked eye at the clear visual distance (250mm) [3-5]. But in the application of the microscope, total magnification of microscope is the ratio of the virtual image length or height that the object is viewed through eyepieces of microscope and the actual length or height of the same object. In this paper, the method of measuring the actual total magnification of metallographic microscope just is based on this one characteristic of practical application.
In 1984, Ma Hui, a Chinese Metallurgical worker, reported the measuring method of the actual magnification of the metallographic microscope measured with a self-made measuring device. In 1998, the ASTM issued the Standard Guide for Calibrating Reticles and Light Microscope Magnifications, there are 4 revisions to 2014, and the method of measurement is basically the same as that reported by Ma Hui, however the measurement accuracy is improved by measuring the distance between the observation point and the eyepiece. But the measurement magnification using the ASTM standard method isn’t the magnification of virtual image that is magnified two times and is viewed through eyepieces of microscope, it is the magnification of true image that is magnified two times and the true image is projection image taking the eyepiece as the photographic eyepiece. The measurement result just is the lateral magnification of projection image and it isn’t the actual total magnification of the virtual image that is viewed through eyepieces of microscope.

By viewing ocular micrometer and stage micrometer through eyepieces of microscope, it can be found that the actual magnification of micrometer and theoretical magnification cannot be consistent. It is difficult to determine that the deviation is from the objectives, tube factor or the eyepiece. The image observed in the microscope eyepiece is the virtual image of sample that is putted on the object table and it is magnified by the objective lens and the eyepiece. The virtual image is 250 mm away from the eyes. The total magnification of the microscope is the visual magnification of the image that is 250 mm away from the eyes [1, 8-9]. The actual total magnification of microscope should be measured by comparing the length of length scale at 250mm.

In this paper, a digital camera system is used as eyes; Leitz MM6 metallographic microscope on site is applied. The image that is viewed in the eyepiece and the image of gauge block at 250 mm away from the camera are viewed, acquired and recorded at the same acquiring conditions. The two digital images are measured and compared in the same measuring system. Then the magnification of eyepieces, objectives and tube factor, and the actual total magnification of metallographic microscope are calculated. The new measurement method of magnification is consistent with the practical using of microscope, and the new measurement method and the uncertainty of measurement results are studied.

2. Basic Principle of Measurement
A digital camera acquiring system is used as eyes, the digital image of ocular micrometer and objective micrometer that viewed in the eyepiece of microscope is acquired, the digital image of gauge block at 250 mm away from the camera is acquired, the diagram of acquiring digital image for measurement see Figure 1. The same actual length AB being in two digital images are measured by image analysis software. The expressions for eyepiece magnification and actual total magnification of microscope are shown in Eq 1 and Eq 2.

\[
M_1 = \frac{L_1}{L_0} \quad (1)
\]

\[
M_2 = \frac{L_2}{L_0} \quad (2)
\]

\(AB\) is the actual length, mm; \(L_1\) is \(AB\) image length that is in the eyepiece and is magnified by the eyepiece, pixel; \(L_2\) is \(AB\) image length that is in the eyepiece and is magnified by the eyepiece and objectives, pixel; \(L_0\) is \(AB\) image length that is at 250 mm away from digital camera, pixel; \(M_1\) is the eyepiece magnification, \(\times\); \(M_2\) is the actual total magnification of microscope, \(\times\).
1. Acquiring digital image for micrometer of microscope

2. Acquiring digital image for gauge blocks

**Figure 1.** The diagram of acquiring digital image for measurement.

In the digital image with ocular micrometer and stage micrometer, the actual specific length is $CD$ and the unit is pixel, the $CD$ is measured individually with ocular micrometer and stage micrometer. The expression for objectives and tube factor magnification is shown in Eq 3.

$$M3 = \frac{h1}{h2}$$

Which: $h1$ is the CD measurement result using ocular micrometer, pixel; $h2$ is the CD measurement result using objective micrometer, pixel; $M3$ is the magnification of objective and tube factor, $\times$.

3. Measurement System Requirements

The measurement system for measuring the actual total magnification of the microscope needs to meet the following requirements: 1) the calibrated and 5 grade gauge block. Its standard length is 0.5 mm to 100 mm and the standard length can be selected according to the microscope magnification planning to measure $^{10}$; 2) The calibrated micrometer. The stage micrometer type is 1/100 and the scale division is 0.01 mm, the ocular micrometer type is 5/100 or 10/100 and the scale division is 0.05 mm or 0.1 mm $^{11}$; 3) The digital camera should be able to acquire the 5 mm length of ocular micrometer at least, and should clearly distinguish the 0.5 mm gauge block at 250 mm ± 3 mm away from digital camera, and should clearly distinguish the 0.01 mm scales of stage micrometer in the eyepiece, and should clearly distinguish the 0.05 mm scales of ocular micrometer in the eyepiece. The digital image should be in focus, no visual aberration and no visual distortion. The 0.5 mm length in the gauge block digital image is not less than 5 pixel; 4) The measurement software should be able to measure the pixel of 0.01 mm length in the stage micrometer digital image, and should be able to measure the pixel of 0.5 mm length in the gauge block digital image.
In this paper, the measurement system includes the following: 0.5mm length and 5 degrade gauge block; 5mm length and 5 degrade gauge block; 0.01mm stage micrometer; 0.05mm ocular micrometer; CWF digital camera system, CWF quantitative and semi-quantitative image analysis software; Leiza MM6 metallographic microscope, and tube factor marked magnification is 0.8×, the objective marked magnification is 16×, the eyepiece marked magnification is 12.5×, and the theoretical magnification is 160×.

4. Measurement Method and Uncertainty Evaluation of Measurement Results

4.1. Image Acquisition of Gauge Block and Uncertainty Evaluation

The image resolution of digital camera is set to be 3488 pixel×2616 pixel. The gauge blocks are placed in the right ahead of the camera and the distance between the camera and gauge blocks are 250 mm, and they are in the center of the digital image. The image of 0.5 mm and 5 mm gauge blocks is acquired by the digital camera acquisition system, see Figure 2.

Figure 2. The digital image of gauge blocks at 250 mm away from camera.

In the same way, the 0.5 mm and 5 mm gauge blocks are placed in the right ahead of the camera and the distance between the camera are 244 mm, 247 mm, 253 mm, and 256 mm, respectively. The gauge blocks are acquired by the digital camera acquisition system. The lengths of gauge blocks in the digital images are measured, respectively. The measurement results are shown in Table 1.

Table 1. The measurement results of gauge blocks images at different distances.

| distance / mm | 244   | 247   | 250   | 253   | 256   |
|---------------|-------|-------|-------|-------|-------|
| 0.5 mm gauge block /pixel | 7.61  | 6.81  | 7.21  | 6.81  | 7.21  |
|                | 6.01  | 6.81  | 6.40  | 5.60  | 6.80  |
|                | 7.21  | 6.41  | 6.01  | 6.81  | 6.81  |
|                | 7.61  | 7.20  | 6.40  | 6.00  | 6.80  |
|                | 7.60  | 7.61  | 7.20  | 6.41  | 7.21  |
| Avg. /pixel    | 7.209 | 6.969 | 6.645 | 6.327 | 6.967 |
| standard deviation /pixel | 0.691 | 0.454 | 0.536 | 0.527 | 0.223 |
|                | 68.00 | 68.40 | 66.80 | 66.00 | 64.90 |
|                | 68.00 | 68.81 | 66.00 | 66.80 | 65.34 |
| 5 mm gauge block /pixel | 68.00 | 68.00 | 66.80 | 66.00 | 65.33 |
|                | 65.34 | 67.20 | 66.40 | 66.80 | 64.00 |
|                | 63.34 | 68.00 | 66.00 | 65.60 | 64.45 |
| Avg. /pixel    | 66.537| 68.081| 66.400| 66.240| 64.802|
| standard deviation /pixel | 2.126 | 0.596 | 0.400 | 0.537 | 0.580 |
For the measurement of 0.5 mm gauge length in the digital image using software, there are 3 main sources of uncertainty [12-16]. The first, the uncertainty ($u_1$) is from repeated measurement: the average value of 5 times measurement results is 6.645 pixel, the standard deviation ($s$) is 0.536 (see Table 1), and thus the uncertainty ($u_1$) is 0.240; The second, the uncertainty ($u_2$) is from gauge block: for the 5 grade gauge block, the extended uncertainty ($U$) is 0.0006, the extended factor ($k$) is 2, the dates are from the calibration certificate; the conversion factor from 0.5mm to 6.645 pixel is 13.29, and thus the uncertainty ($u_2$) is 0.004 (13.29×0.0006/2); The last, the uncertainty ($u_3$) is from distance deviation of image acquisition: within the range of 250 mm±3mm, the maximum measurement value of 0.5mm gauge block is 6.969 pixel, the minimum value is 6.327 pixel, the range is 0.642 pixel (see Table 1), the range coefficient is 1.69, and thus the uncertainty ($u_3$) is 0.340 (0.642/1.69). The combined standard uncertainty can then be calculated as follows.

$$u_c = \sqrt{u_1^2 + u_2^2 + u_3^2} = \sqrt{0.240^2 + 0.004^2 + 0.340^2} = 0.42$$

For 0.5 mm gauge block, the measurement results of length are 6.65(0.42) pixel and the relative uncertainty is 6.3%.

He uncertainty of length measurement result of 5 mm gauge block is evaluated by using the same method, and the combined standard uncertainty ($u_c$) is 0.48 pixel. For 5 mm gauge block, the measurement results of length are 66.40(0.48) pixel. And the relative uncertainty is 0.73%.

4.2. Image Acquisition of Micrometer and Uncertainty Evaluation

The objectives lens and eyepiece are mounted on the microscope and the 1/100 stage micrometer is putted on the object table. The height of the object table is adjusted until there is clear image of 1/100 stage micrometer and 5/100 ocular micrometer. The clear image is acquired by digital camera acquisition system through eyepiece, see Figure 2. The black scale is 5/100 ocular micrometer and the white scale is 1/100 stage micrometer.

![Figure 3. The micrometer digital image acquired through eyepieces.](image)

The image is acquired 5 times. The same length in the images is repeatedly measured 5 times. The measurement results of 5mm length of 5/100 ocular micrometer are shown in Table 2.
Table 2. The 5 mm length measurement results of 5 ocular micrometer images.

| Image | No.1 | No.2 | No.3 | No.4 | No.5 |
|-------|------|------|------|------|------|
|       | 902.44 | 905.82 | 922.95 | 890.44 | 902.17 |
|       | 902.44 | 907.50 | 922.81 | 890.41 | 904.42 |
| Repeated measures /pixel | 900.05 | 904.32 | 921.45 | 890.41 | 900.31 |
|       | 902.44 | 907.23 | 920.22 | 891.21 | 903.50 |
|       | 902.43 | 906.90 | 921.58 | 889.62 | 902.17 |
| Avg. /pixel | 901.96 | 906.35 | 921.80 | 890.42 | 902.51 |
| relative standard deviation $s_{rel}$ /pixel | 0.12% | 0.14% | 0.12% | 0.06% | 0.17% |
| combined relative standard deviation $s_{p-rel}$ /pixel | 0.129% |

In the actual measurement, the measurement result is from the one image and 5 times measurement for the same length. In this paper, the 160× measurement results of the MM6 metallographic microscope are follows.

The 5 times measurement results of 5mm length of 5/100 ocular micrometer use the measurement results of the No.3 image, the average is 921.80 pixel (see Table 2). By calculating, the conversion factor of 5/100 ocular micrometer from 5mm to 921.80 pixel is 184.4, and the millimeter - to - pixel conversion can be calculated as follows.

$$y = f(x) = 184.4x$$ (4)

The 5 times measurement result of 0.5mm length of 1/100 stage micrometer are 1030.80 pixel, 1029.50 pixel, 1029.50 pixel, 1029.60 pixel, and 1029.60 pixel, the average is 1029.80 pixel. By calculating, the conversion factor of 1/100 stage micrometer from 0.5 mm to 1029.80 pixel is 2059.60 and the millimeter - to - pixel conversion can be calculated as follows.

$$y = f(x) = 2059.60x$$ (5)

For the measurement of 5 mm length of ocular micrometer, there are 2 main sources of uncertainty. The first, the uncertainty ($u_1$) is from repeated measurement for repeatedly acquired images, and it is the combined standard deviation of single measurement value. Selecting the measurement results of the No.3 image, the average value is 921.80 pixel, he combined standard deviation is 0.129%, and thus the uncertainty ($u_1$) is 1.19 (921.80×$s_{p-rel}$=921.80×0.129%), see Table 2; The other, the uncertainty ($u_2$) is from the 5 mm ocular micrometer: for the ocular micrometer, the extended uncertainty ($U$) is 0.0005, the extended factor ($k$) is 2, the dates are from the calibration certificate; the conversion factor from millimeter to pixel is 184.4, see Eq 4, and thus the uncertainty ($u_2$) is 0.046 (184.4×0.0005/2). The combined standard uncertainty can then be calculated as follows.

$$u_e = \sqrt{u_1^2 + u_2^2} = \sqrt{1.19^2+0.046^2}=1.19$$

For 5/100 ocular micrometer, the measurement results of 5mm length are 921.8(1.2) pixel.

The uncertainty of 0.5mm length measurement results of 1/100 stage micrometer is evaluated by using the same method, and the combined standard uncertainty ($u_e$) is 1.4 pixel. For 1/100 stage micrometer, the measurement results of 0.5mm length are 1029.8(1.4) pixel.

4.3. Pixel to Millimeter Conversion

According to the pixel range of micrometer (see Figure 2), 800 pixel length is selected. For ocular micrometer, the millimeter length of 800 pixel length is 4.338 mm by means of the Eq 4. For stage micrometer, the millimeter length of 800 pixel length is 0.388 mm by means of the Eq 5.

The 5 points around the 4.338 mm of ocular micrometer are selected, and the 5 points pixel length is measured. They are 4.25 mm, 4.30 mm, 4.35 mm, 4.40 mm, and 4.45 mm, and the measurement
results see Table 3. The pixel-to-millimeter conversion can be calculated as follows based on linear-regression analysis.

\[ y = 185.4x - 4.385 \]  

(6)

The millimeter length of 800 pixel length is 4.337 mm by means of the Eq 6, and the uncertainty that is from linear-regression analysis is 0.014, and the relative uncertainty is 0.32% [12-15]. For 5/100 ocular micrometer, the measurement results of 800 pixel are 4.337(0.014) mm.

The 5 points around the 0.388 mm of stage micrometer are selected, and the 5 points pixel length is measured. They are 0.37 mm, 0.38 mm, 0.39 mm, 0.40 mm, and 4.41 mm, and the measurement results see Table 4. The pixel-to-millimeter conversion can be calculated as follows based on linear-regression analysis.

\[ y = 2070.62x - 5.3962 \]  

(7)

The millimeter length of 800 pixel length is 0.3890 mm by means of the Eq 7 and the uncertainty that is from linear-regression analysis is 0.0015, and the relative uncertainty is 0.39% [12-15]. For 1/100 stage micrometer, the measurement results of 800 pixel are 0.3890(0.0015) mm.

### Table 3. Ocular micrometer millimeter-pixel regression analysis data.

| distance /mm | 4.25  | 4.30  | 4.35  | 4.40  | 4.45  |
|--------------|-------|-------|-------|-------|-------|
| Repeated measures /pixel | 783.27 | 793.19 | 803.10 | 812.10 | 821.05 |
|              | 783.24 | 793.17 | 802.11 | 812.04 | 821.01 |
|              | 784.18 | 792.20 | 803.16 | 812.10 | 820.06 |
|              | 783.20 | 794.17 | 801.13 | 812.06 | 820.06 |
|              | 784.24 | 793.17 | 802.13 | 811.04 | 821.05 |
| Avg. /pixel  | 783.63 | 793.18 | 802.33 | 811.87 | 820.65 |

### Table 4. Stage micrometer millimeter-pixel regression analysis data.

| distance /mm | 0.37  | 0.38  | 0.39  | 0.40  | 0.41  |
|--------------|-------|-------|-------|-------|-------|
| Repeated measures /pixel | 760.13 | 780.11 | 803.12 | 822.07 | 843.12 |
|              | 762.17 | 783.08 | 802.14 | 822.22 | 845.17 |
|              | 760.13 | 781.09 | 802.05 | 822.01 | 844.06 |
|              | 760.01 | 781.01 | 803.16 | 822.16 | 844.24 |
|              | 761.08 | 781.16 | 803.06 | 823.02 | 842.07 |
| Avg. /pixel  | 760.70 | 781.29 | 802.71 | 822.30 | 843.73 |

### 4.4. Magnification Measurement and Evaluation of Uncertainty

#### 4.4.1. Eyepiece Magnification

The maximum length of the ocular micrometer is 5 mm (see Figure 3), take AB=5 mm. The L0 measurement results of the 5 mm gauge are 66.40(0.48) pixel (see Figure 2 and see 4.1). The L1 measurement results of the 5 mm length of ocular micrometer are 921.8(1.2) pixel (see Figure 3 and see 4.2). According to the Eq 1, the actual magnification (M1) and it’s the relative uncertainty (u) of the eyepiece can then be calculated as follows.

\[ M1 = L1/L0 = 921.8/66.4 = 13.88 \times \]

\[ u_{L0-ref} = \sqrt{u_{L1-ref}^2 + u_{L0-ref}^2} = \sqrt{\left(\frac{0.48}{66.4}\right)^2 + \left(\frac{1.2}{921.8}\right)^2} = 0.74\% \]
The eyepiece marked magnification is 12.5×, the measurement result is 13.88×, the relative deviation is 11%, and the relative uncertainty is 0.74%.

4.4.2. Objectives and Tube Factor Magnification. For 800 pixel length, the \( h_1 \) measurement results of ocular micrometer are 4.337(0.014) mm, and the \( h_2 \) measurement results of stage micrometer are 0.3890 (0.0015) mm (see Figure 3 and see 4.3). According to the Eq 3, the actual magnification (\( M_3 \)) and it’s the relative uncertainty (\( u \)) of the objectives and tube factor can then be calculated as follows.

\[
M_3 = \frac{h_1}{h_2} = \frac{4.337}{0.3890} = 11.15 \, (\times)
\]

\[
\begin{align*}
\text{\( u_{\text{rel}} = \sqrt{u_{h1-ref}^2 + u_{h2-ref}^2} = \sqrt{\left(\frac{0.014}{4.337}\right)^2 + \left(\frac{0.0015}{0.3890}\right)^2} = 0.52\% \}}
\end{align*}
\]

The objectives and tube factor theoretical magnification is 16×0.8, the measurement result is 11.15×, the relative deviation is -13%, and the relative uncertainty is 0.52%.

4.4.3. Actual Total Magnification. The maximum length of the stage micrometer is 0.5 mm (see Figure 3), take AB=0.5 mm. The \( L_0 \) measurement results of the 0.5mm gauge are 6.65(0.42) pixel (see Figure 1 and see 4.1). The \( L_2 \) measurement results of the 0.5mm length of stage micrometer are 1029.8(1.4) pixel (see Figure 3 and see 4.2). According to Eq 2, the actual total magnification (\( M_2 \)) and it’s the relative uncertainty (\( u \)) and extended uncertainty (\( U \)) of the MM6 metallographic microscope 160× can then be calculated as follows.

\[
M_2 = \frac{L_2}{L_0} = \frac{1029.8}{6.65} = 154.86 \, (\times)
\]

\[
\begin{align*}
\text{\( u_{\text{rel}} = \sqrt{u_{L2-ref}^2 + u_{L0-ref}^2} = \sqrt{\left(\frac{1.4}{1029.8}\right)^2 + \left(\frac{0.42}{6.65}\right)^2} = 6.3\% \}}
\end{align*}
\]

\[
U = 154.86 \times 6.3\% \times 2 = 20, \, k=2
\]

The relative deviation of 160× is -3.2%.

For MM6 metallographic microscope, the 160× measurement results of actual total magnification are stated as follows.

\[ 155\times, \, U=20\times, \, k=2 \]

According to the ISO 8039 standards [3] and ASTM E1951 standards [7], the actual total magnification can be calculated as follows.

\[
M = M_1 \times M_3 \quad (8)
\]

According to the \( M_1 \) and \( M_3 \) measurement results (see 4.4.1 and 4.4.2), the actual total magnification (\( M \)) and it’s the relative uncertainty (\( u \)) and extended uncertainty (\( U \)) of the MM6 metallographic microscope 160× can then be calculated as follows.

\[
M = 13.89 \times 11.15 = 154.78 \, (\times)
\]

\[
\begin{align*}
\text{\( u_{\text{rel}} = \sqrt{u_{M1-ref}^2 + u_{M3-ref}^2} = \sqrt{(0.74\%)^2 + (0.52\%)^2} = 0.90\% \}}
\end{align*}
\]

\[
U = 154.78 \times 0.90\% \times 2 = 2.8, \, k=2
\]

The relative deviation of 160× is also -3.2%.

For MM6 metallographic microscope, the 160× measurement results of actual total magnification are stated as follows based on the Eq 8.

\[ 154.8\times, \, U=2.8\times, \, k=2 \]

5. Analyses and Discussion
In Figure 3, if the magnifications of objectives, tube factor, and eyepiece were equal to the actual magnifications, and if the 0 marks of ocular micrometer and stage micrometer were at the same site,
the 0.39 mm of stage micrometer that was amplified by 16×0.8 (12.8×) and the 5 mm of ocular micrometer were at the same site. In fact, the 0.45 mm of stage micrometer and the 5 mm of ocular micrometer are at the same site. The one of purpose of this paper is to search the practical and basic causes.

According to the measurement results, the magnification deviation of the eyepiece, objectives and tube factor of the MM6 metallographic microscope are larger. The actual magnification of 12.5× eyepiece is 13.88×, and the relative deviation is 11%. The actual magnification of 16× objectives and 0.8× tube factor (12.8×) is 11.15×, and the relative deviation is -13%. These are exactly the main causes that the 0.39 mm of stage micrometer and the 5 mm of ocular micrometer wasn’t at the same site in Figure 3. In the practical application of a metallographic microscope, the eyepiece or objectives is not used alone. In the case of the actual total magnification to meet the requirements, the actual deviation of the objectives and eyepiece will not affect the use of the metallographic microscope. For the MM6 large metallographic microscope, there are projection screen, 135 camera, video camera, and naked eye view 4 optical paths. The determination of the marked magnification of the objectives and eyepiece may take into account the overall optical paths of the microscope in order to ensure the actual total magnification of the 4 paths. It also shows that the lenses of different microscopes are not interchangeable.

In addition, the ISO 8578 standard [16] specifies the magnification marking requirements of the microscope objectives and eyepiece, there are no requirements for the actual deviation of the magnification and there are no marking requirements of tube factor. According to the total magnification calculation equation that is stated in the ISO 8039 standard [3], ASTM E1951 standard [7], and GB/T 22059 standard [17], the default tube factor is typically 1. The 5.1.1 requirements of ASTM E1951 standard also clearly pointed out: A calculated magnification, using the manufacturer’s supplied ratings, is only an approximation of the true magnification, since individual optical components may vary from their marked magnification. In this sense, it is very necessary to measure the actual total magnification of the microscope.

In this paper, the theoretical magnification of MM6 metallographic microscope is 160×. According to the Eq 2, the actual total magnification is 155×, and the relative deviation is -3.2%. According to the Eq 8, the actual total magnification is 154.9×, and the relative deviation is also -3.2%. The two measurement results are equal, thus the digital image method to measure the actual total magnification of metallographic microscope should be reliable.

For 160× measurement of MM6 metallographic microscope, the direct measurement parameter, measurement results, and the uncertainty of the measurement results are shown in Table 5. The measurement results and their uncertainty of eyepiece magnification, objectives and tube factor magnification, and the actual total magnification of microscope are shown in Table 6.
Table 5. Summary table of measurement parameter, results, and uncertainty.

| parameter                  | symbol | unit | Avg. | uncertainty component                  | combined uncertainty | relative uncertainty |
|----------------------------|--------|------|------|----------------------------------------|----------------------|----------------------|
| 0.5 mm gauge block         | L0     | pixel | 6.65 | Repeated measures calibration certificate distance deviation repeated measures calibration certificate distance deviation repeated measures calibration certificate distance deviation | 0.42                 | 6.3%                 |
| 5 mm gauge block           | L0     | pixel | 66.40| repeated measures                       | 0.48                 | 0.73%                |
| 0.5 mm micrometer (1/100)  | L2     | pixel | 1029.8| repeated measures calibration certificate distance deviation repeated measures calibration certificate distance deviation repeated measures calibration certificate distance deviation | 1.4                  | 0.14%                |
| 5 mm micrometer (5/100)    | L1     | pixel | 921.8| repeated measures                       | 1.2                  | 0.13%                |
| ocular micrometer 800 pixel| h1     | mm   | 4.337| linear-regression analysis              | 0.014                | 0.32%                |
| objective micrometer 800 pixel| h2   | mm   | 0.3890| linear-regression analysis              | 0.0015               | 0.39%                |

Table 6. Summary table of magnification and uncertainty.

| unit: ×                      | symbol | result | relative component | uncertainty | relative combined uncertainty |
|-------------------------------|--------|--------|--------------------|-------------|-------------------------------|
| eyepiece magnification (Eq.1, AB=5 mm) | M1     | 13.88  | L1                 | 0.13%       | 0.74%                         |
|                               |        |        | L0                 | 0.73%       |                               |
| actual total magnification (Eq.2, AB=0.5 mm) | M2     | 155    | L2                 | 0.14%       | 6.3%                          |
|                               |        |        | L0                 | 6.30%       |                               |
| objectives and tube factor magnification (Eq.3, CD=800 pixel) | M3     | 11.15  | h1                 | 0.35%       | 0.52%                         |
|                               |        |        | h2                 | 0.39%       |                               |
| actual total magnification (Eq.8 or Eq.9) | M      | 154.8  | M1                 | 0.74%       | 0.90%                         |
|                               |        |        | M3                 | 0.52%       |                               |

According to the results of measurement uncertainty evaluation, the main sources of the uncertainty are from the measuring of the 0.5 mm gauge digital image. Its relative standard uncertainty is 6.3%, and it leads to result that the actual total magnification measurement results of the relative uncertainty is 6.3%. For the 0.5 mm gauge block, although the uncertainty would be reduced by increasing the resolution of the digital camera acquisition system, this methods could not reduce the uncertainty to a great extent, because the gauge block acquired distance are at 250 mm away from camera and the ratio of length to distance is 1:500 (0.5:250). Comparing using equation 8 with equation 2, the two measurement results are equal, but the relative standard uncertainty is reduced from 6.3% to 0.90%, and the uncertainty is reduced by a factor of 7. Thus the best measurement method is stated as follows. The first, the eyepiece magnification is measured by means of measuring digital image of 5 mm gauge block and 5/100 ocular micrometer. The second, the objectives and tube factor magnification is measured by means of measuring digital image of ocular micrometer and stage micrometer. The last,
the actual total magnification of the microscope is calculated, it is the product of eyepiece magnification and objectives and tube factor magnification. For 160× of MM6 metallographic microscope, the best measurement results are stated as follows.

\[ 154.8\times, \quad u_{\text{ref}} = 0.90\%, \quad U_{\text{ref}} = 1.8\%(k=2), \quad U = 2.8\times(k=2) \]

Based on this, the expression for measuring and calculating the actual total magnification of the metallographic microscope is shown in Equation 9.

\[ M = M_1 \times M_3 = (L_1 \times h_1)/(L_0 \times h_2) \] (9)

Which: 1) \( M \) is the actual total magnification of the microscope, \( x \); 2) \( L_1 \) is the 5 mm length of 5 mm ocular micrometer digital image acquired through eyepiece, pixel; \( L_0 \) is the 5 mm length of 5 mm gauge block digital image acquired at 250 mm away from the digital camera, pixel; 3) \( L \) is selected length of 1/100 stage micrometer digital image acquired through eyepiece, pixel. \( h_1 \) is the length of the ocular micrometer corresponding to \( L \), mm; \( h_2 \) is the length of the stage micrometer corresponding to \( L \), mm.

In the ISO 8039 standard [3], ASTM E1591 standard [7] and GB/T 22059 standard [17], the magnification of the microscope is defined, and the total magnification of the microscope is shown in Eq 10.

\[ M_{\text{TOTVIS}} = M_O \times q \times M_E \] (10)

Which: \( M_{\text{TOTVIS}} \) is the total magnification of the microscope. \( M_O \) is the objectives magnification. \( q \) is the total tube factor. \( M_E \) is the eyepiece magnification.

The ISO 8039 standard [3] and GB/T 22059 standard [17] also specify that the objectives magnification tolerance is ±5%, the tube factor tolerance is ±2%, and the eyepiece magnification tolerance is ±5%. In this way, if the objectives, tube factor, and eyepiece meet the requirements, the maximum positive deviation and negative deviation of microscope magnification would be calculated as follows.

\[ (1.05 \times 1.02 \times 1.05 - 1)/1 = 12.455\%. \]
\[ (0.95 \times 0.98 \times 0.95 - 1)/1 = -11.555\% \]

Thus, the microscope allowable value of actual total magnification would be calculated as follows.

\[ 12.455\% + 11.555\% = 24.01\% \]

For measurement 160× of MM6 metallographic microscope, the uncertainty of measurement result is 0.90%. Without considering the uncertainty of repeated measurements, the maximum uncertainty of the digital image method measurement system can be considered as 0.90%. The ratio of measurement system uncertainty to microscope allowable value of actual total magnification would be calculated as follows.

\[ 0.90\%: 24.01\% \approx 1:27 \]

The ratio of 1:27 is smaller than the ratio of 1:10 that is specified by the ISO 15227 standard [5]. In the same way, the eyepiece allowable value is 10%, and the objectives and tube factor allowable value is 14%, the maximum uncertainty (0.9%) of the digital image method measurement system is smaller than 10% of eyepiece allowable value (10%) and objectives and tube factor allowable value (14%). This further shows that the digital image method is reliable for measuring the actual total magnification of metallographic microscope and it can be a standard measurement method. It is necessary to further standardize the study. It is necessary to further study for standardization for the digital image method.

6. Conclusions

By using the method of digital image, the actual total magnification of 160× of MM6 metallographic microscope is measured, and the uncertainty of the measurement result is evaluated. The following
conclusions can be drawn:

(1) The digital images of 5/100 ocular micrometer and 1/100 stage micrometer in the eyepieces of microscope are acquired, and the digital images of the 5 grade gauge block that the length is 5 mm and is from camera 250 mm in the same acquiring conditions are acquired. The lengths of the ocular micrometer and gauge block in the digital image are measured, and then the magnification of eyepieces is calculated. The lengths of the eyepieces and stage micrometer in the same digital image are measured, and then the magnification of objectives and tube factor is calculated. The actual total magnification of metallographic microscope is the product of magnification of eyepieces and magnification of objectives and tube factor.

(2) For 160× of MM6 metallographic microscope, the measurement result of actual total magnification is stated as follows: 154.8×, \( U=2.8\times \), \( k=2 \), and the actual relative deviation is -3.2%.

(3) The digital image measuring method for actual total magnification of metallographic microscope can be a standardized method.

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