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Error Analysis and Amendment on Magnesium Alloy's Ignition Temperature Test System Based on Two-color Method

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Abstract: Measuring magnesium alloy's ignition temperature with a thermocouple had the disadvantages of slow response speed, interfering temperature field, low accuracy, etc, magnesium alloy's ignition temperature test system based on two-color method was designed, ignition time was located according to inflexion of radiation energy. First, emissivity test experiment was designed, magnesium alloy was heated relaxedly by current heating method, measured value of C-type thermocouple was divided by measured value of high-speed industrial grade infrared ray transmitter OS4000 to determine material's emissivity, the emissivity at the temperature approximating to magnesium alloy's ignition value was used to amend measured value of OS4000; after that, magnesium alloy was ignited by current heating method, the relative error between ignition temperature test system's result and OS4000 result was 2.67 %; at last, in order to improve temperature-measuring accuracy, the emissivity ratio corresponding to two wavelengths at the temperature approximating to magnesium alloy's ignition value was amended, results show that, temperature-measuring accuracy is 0.76 % after amending. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Two-color method, Ignition temperature, Emissivity ratio amendment, Current-heating method, Magnesium alloy.

1. Introduction

Magnesium alloy has low density and is usually used in engine and instruments to reduce dead weight, low elasticity modulus can help absorb shake and noise to avoid damaging components, good machinability makes it easy to get slippy and neat surface, waste magnesium alloy can be recycled [1]. However, chemical property of magnesium is very active and density coefficient of oxide film MgO is 0.79, according to Pilling-Bedworth oxidation film principle [2], MgO film does not play a protective role, which hinders the application of magnesium alloy.

Ignition-proof magnesium alloy technology [3-5] can enhance magnesium alloy's ignition temperature and solve this problem; one important characterization parameter of this technology is ignition temperature.

With thermocouples [6] used as temperature-measuring tool at home and abroad, with the help of various kinds of constant temperature furnace [7-9], ESD principle [10], heated filament [11] and stuff like that to ignite magnesium alloy, ignition was located by tangent method, which had slow response speed, had low experiment efficiency and interfered temperature field. Magnesium alloy's ignition temperature test system based on two-color was designed, ignition time was located according to inflexion of radiation energy because magnesium alloy released a lot of heat when it started to burn, experiments were designed to get approximate value of magnesium alloy' emissivity at its ignition temperature, then two wavelengths' emissivity ratio was amended.

This method not only eliminated the interference caused by emissivity changes but also had merits of high response speed, high accuracy and high experiment efficiency.

2. Magnesium Alloy's Ignition Temperature Test System Based on Two Color Method

Magnesium alloy's ignition temperature test system based on two-color was shown in Fig. 1, including sapphire, lens system, dual-quadrant detector covered by one optical filter whose wavelength was 650±30 nm on the left side and the other whose wavelength was 850±30 nm on the right side, conditioning circuit, using a high temperature resistant round shell to package and fix them. Sapphire protected all the parts of this shell from damaging by high temperature; lens system focused light radiation, making them project on the whole active surface of dual-quadrant detector; dual-quadrant detector changed light signal to light current (microamp level), linking N poles of four photodiodes to copper-clad plate as common N pole, P poles of the top and bottom photodiodes on each side were linked respectively to enlarge active area and increase received signal intensity, then each side was covered by two optical filters respectively, realizing systematic miniaturization; conditioning circuit amplified and filtered tiny light current signals to output voltage.

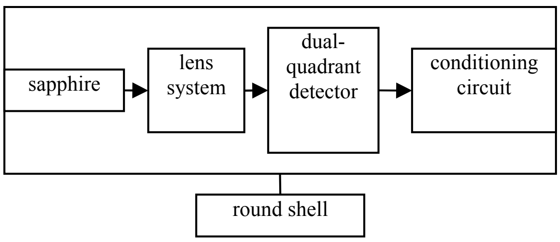

Fig. 1. Functional block diagram of magnesium alloy's ignition temperature test system based on two-color.

3. Systematic Temperature-measuring Theory

Dual-quadrant detector turned received two-way radiation energy into two light current, according to Planck law, we can get

$$R(T)=\frac{I_1(T)}{I_2(T)} =\frac{S(\lambda_1)\times\psi(\lambda_1)\times\tau(\lambda_1)\times\varepsilon(\lambda_1,T)\times\int_{\lambda_1-\Delta\lambda/2}^{\lambda_1+\Delta\lambda/2}\frac{C_1}{\lambda^5 e^{C_2/\lambda_1 T}}d\lambda}{S(\lambda_2)\times\psi(\lambda_2)\times\tau(\lambda_2)\times\varepsilon(\lambda_2,T)\times\int_{\lambda_2-\Delta\lambda/2}^{\lambda_2+\Delta\lambda/2}\frac{C_1}{\lambda^5 e^{C_2/\lambda_2 T}}d\lambda}, \tag{1}$$

where $R(T)$ is the radiation power ratio of two waveband, $I_1(T)$ and $I_2(T)$ is the light current outputted from dual-quadrant detector, $\Delta\lambda$ is the bandwidth of chosen optical filter, $S(\lambda)$, $\Psi(\lambda)$ and $\tau(\lambda)$ are the optical system's spectrum transmittance, narrow-band interference filter's spectrum transmittance and dual-quadrant detector's response function. Order

$$K=\frac{S(\lambda_1)\times\psi(\lambda_1)\times\tau(\lambda_1)\times\varepsilon(\lambda_1,T)}{S(\lambda_2)\times\psi(\lambda_2)\times\tau(\lambda_2)\times\varepsilon(\lambda_2,T)}, \tag{2}$$

$$R_1(T)=\frac{\int_{\lambda_1-\Delta\lambda/2}^{\lambda_1+\Delta\lambda/2}\frac{C_1}{\lambda^5 e^{C_2/\lambda_1 T}}d\lambda}{\int_{\lambda_2-\Delta\lambda/2}^{\lambda_2+\Delta\lambda/2}\frac{C_1}{\lambda^5 e^{C_2/\lambda_2 T}}d\lambda}, \tag{3}$$

then

$$R(T)=K\cdot R_1(T), \tag{4}$$

When confirming two wavelengths and doing static calibration on this system, $\varepsilon(\lambda_1,T)\approx\varepsilon(\lambda_2,T)$, K was deemed to be a constant, finally we determined $K=23.08$ by use of medium temperature blackbody furnace to calibrate the system [12].

After completing formula transformation by formula (1) ~ (4) and taking the logarithm of formula (4), we obtain that

$$\ln\frac{R(T)}{K}=\ln\frac{\int_{\lambda_1-\Delta\lambda/2}^{\lambda_1+\Delta\lambda/2}\lambda^{-5}d\lambda}{\int_{\lambda_2-\Delta\lambda/2}^{\lambda_2+\Delta\lambda/2}\lambda^{-5}d\lambda}-\frac{\frac{C_2}{\lambda_1}-\frac{C_2}{\lambda_2}}{T}, =\ln A-\frac{B}{T} \tag{5}$$

where $A=3.828$，$B=5208$, then

$$T(°C) = \frac{B}{\ln A - \ln \frac{R(T)}{K}} \text{-273.16}, \quad (6)$$

As longs as we know $R(T)$, temperature value could be gained via formula (6) rather than positioning and reading a value from $R(T)-T$ curve.

4. Material's Emissivity Test

In magnesium alloy's ignition temperature test, we needed temperature-measuring value of high-speed industrial-level fiber infrared ray transmitter OS4000 as standard value, OS4000 was emissivity-adjustable monochrome radiation thermodetector. Temperature accuracy could be guaranteed, only with confirmation of material's emissivity. However, emissivity was easily affected by measured object's temperature, roughness, considered wavelength range, etc. Direct measuring magnesium alloy's emissivity was impossible, as when magnesium started to burn, its warping form was very severe and hard to be fixed, and here we made the following hypothesis (1): when measured magnesium alloy's temperature was close to its ignition, namely, on the verge of igniting but with no sparks, emissivity value was a constant.

4.1. Principle of Material's Emissivity Test

Principle of material's emissivity test was shown as Fig. 2. Agilent direct-current source(hereafter referred to as DC) was linked to stainless steel base by wire, magnesium alloy slice was put on the middle position of stainless steel base, then this slice was heated with current heating method, power increment was applied evenly, output temperature needed some time to reach stabilization, then data could be gathered with C-type thermocouple produced by America Omega Corporation and OS4000, DAC (short for data acquisition card) was linked to a computer to communicate, curve data could be read and processed in Topview software. C-type thermocouple was linked to amplification and filter circuit with the amplification times being 50.

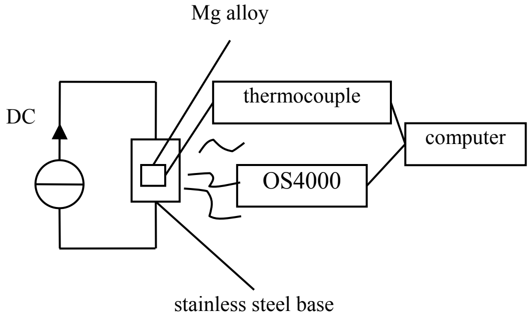

Fig. 2. Functional block diagram of material's emissivity test.

International computational formula to determine material's emissivity was

$$\varepsilon = \frac{T_{\text{real}}}{T_{\text{standard}}} = \frac{T_{OS4000}}{T_{\text{tc}}}, \quad (7)$$

where T_{real} and T_{standard} were temperature values of radiation temperature-measuring instrument (like OS4000) and contact temperature-measuring instrument (like a thermocouple) respectively.

4.2. Data Processing and Analysis Magnesium Alloy's Emissivity Test

Take magnesium alloy (AZ80) as an example, its mass fraction of main chemical component is: Al (7.98 %), Zn (0.45 %), Mn (0.28 %), Cu (0.0049 %), Fe (0.0011 %), Si (0.0068 %), the remaining is nearly Mg. In order to make it be heated quickly and evenly, magnesium alloy was made into slice ($3\times3\times0.25mm^3$).

Emissivity test data of magnesium alloy (AZ80) was shown in Table 1; quadruplet data were acquired before AZ80 began to burn, T_{tc} and T_{OS4000} could be calculated by formula (7).

Results show that, the higher temperature, the higher emissivity, but as a whole, change scope is very small and can be ignored, so hypothesis (1) is tenable.

Finally, the emissivity 0.613 (at the temperature 627.6 °C) is chosen as AZ80's emissivity at its ignition temperature.

Table 1. Emissivity test data of magnesium alloy (AZ80).

$V_{tc.}$(mV)	$T_{tc.}$ (°C)	$V_{OS.}$(V)	$T_{OS.}$ (°C)	ε
488.06	556.8	1.561	334.08	0.6
499.50	568.5	1.622	343.37	0.604
522.75	592.3	1.738	360.71	0.609
557.27	627.6	1.898	384.72	0.613

5. Principle of Magnesium Alloy's Ignition Temperature Test

Functional block diagram of magnesium alloy's ignition temperature test was shown as Fig. 3, DC was linked to stainless steel base by wire, magnesium on the base was heated and ignited by current heating method, power increment was applied evenly, ignition temperature-measuring system and OS4000 were employed to measure temperature, using DAC to communicate with PC and Topview software to gain data. Igniting time was located according to inflexion of output voltage/time curve.

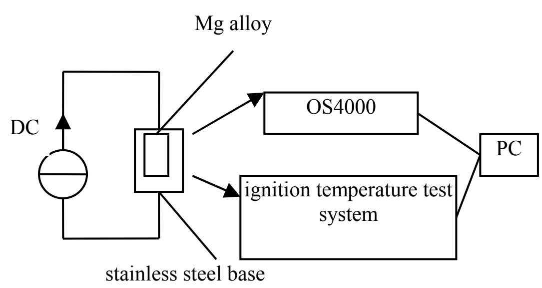

Fig. 3. Functional block diagram of magnesium alloy's ignition test.

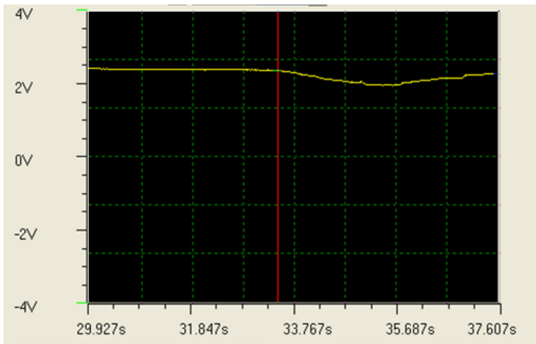

Fig. 5. CH1 curve after low-pass filtering.

5.1. Results and Analysis of Magnesium Alloy's Ignition Temperature Test

Output curve of AZ80's ignition temperature test was shown as Fig. 4, of which CH1 and CH2 were corresponding to output voltage of optical filter whose wavelength were 650 nm and 850 nm respectively, CH3 was regarding to output voltage of OS4000.

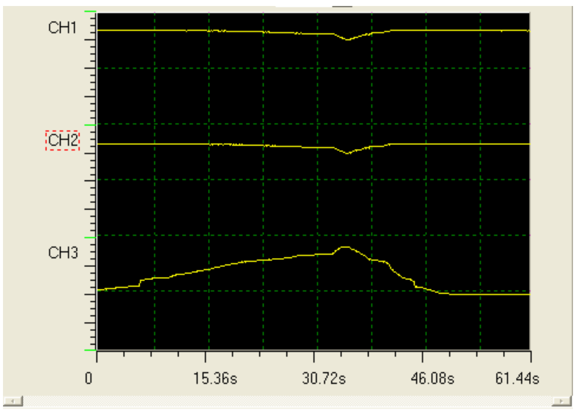

Fig. 4. Output curve of AZ80's ignition temperature test.

Fig. 5 showed the CH1 curve after low-pass filtering. With the help of cursor positioning and reading value, gradient of this curve at 33.227 s suddenly grew, so this time would be the magnesium alloy's ignition time.

Results of AZ80's ignition temperature test was shown in Table 2, ignition temperature of OS4000 and ignition temperature test system are 653.99°C and 671.47°C, whose relative error is 2.67 %. The reason could be that measuring result was supposed to be two-color temperature T_C rather than real temperature T. Emissivity ratio of two wavelengths should be taken into consideration to enhance accuracy.

Table 2. Results of AZ80's ignition temperature test.

CH1 (V)	CH2 (V)	R(T)	CH3 (V)	T_{OS} (°C)	T_C (°C)	δ(%)
2.437	2.14	0.355	2.006	653.99	671.47	2.67

6. Emissivity Ratio Test

In transient temperature measurement, the influence of changing emissivity could not be neglected, emissivity ratio should be amended to two-color temperature T_C, according to formula [13]

$$\frac{1}{T}-\frac{1}{T_C}=\frac{\ln(\varepsilon_{\lambda_1}/\varepsilon_{\lambda_2})}{c_2\left(\frac{1}{\lambda_1}-\frac{1}{\lambda_2}\right)}, \tag{8}$$

6.1. Principle of Emissivity Ratio Amendment

Via emissivity definition and formula (1), (2), (3) and (4), we obtain this

$$\frac{\varepsilon(\lambda_1,T)}{\varepsilon(\lambda_2,T)}=\frac{\int_{\lambda_1-\Delta\lambda}^{\lambda_1+\Delta\lambda}M(\lambda,T)\mathrm{d}\lambda \Big/ \int_{\lambda_1-\Delta\lambda}^{\lambda_1+\Delta\lambda}M_O(\lambda,T)\mathrm{d}\lambda}{\int_{\lambda_2-\Delta\lambda}^{\lambda_2+\Delta\lambda}M(\lambda,T)\mathrm{d}\lambda \Big/ \int_{\lambda_2-\Delta\lambda}^{\lambda_2+\Delta\lambda}M_O(\lambda,T)\mathrm{d}\lambda}=\frac{\dfrac{\int_{\lambda_1-\Delta\lambda}^{\lambda_1+\Delta\lambda}M(\lambda,T)\mathrm{d}\lambda}{\int_{\lambda_2-\Delta\lambda}^{\lambda_2+\Delta\lambda}M(\lambda,T)\mathrm{d}\lambda}}{\dfrac{\int_{\lambda_1-\Delta\lambda}^{\lambda_1+\Delta\lambda}M_O(\lambda,T)\mathrm{d}\lambda}{\int_{\lambda_2-\Delta\lambda}^{\lambda_2+\Delta\lambda}M_O(\lambda,T)\mathrm{d}\lambda}}$$

$$=\frac{\dfrac{S(\lambda_1)\times R(\lambda_1)\times\tau(\lambda_1)\times\int_{\lambda_1-\Delta\lambda}^{\lambda_1+\Delta\lambda}M(\lambda,T)\mathrm{d}\lambda}{S(\lambda_2)\times R(\lambda_2)\times\tau(\lambda_2)\times\int_{\lambda_2-\Delta\lambda}^{\lambda_2+\Delta\lambda}M(\lambda,T)\mathrm{d}\lambda}}{\dfrac{S(\lambda_1)\times R(\lambda_1)\times\tau(\lambda_1)\times\int_{\lambda_1-\Delta\lambda}^{\lambda_1+\Delta\lambda}M_O(\lambda,T)\mathrm{d}\lambda}{S(\lambda_2)\times R(\lambda_2)\times\tau(\lambda_2)\times\int_{\lambda_2-\Delta\lambda}^{\lambda_2+\Delta\lambda}M_O(\lambda,T)\mathrm{d}\lambda}}=\frac{R(T)}{R_O(T)} \tag{9}$$

where $\int_{\lambda_1-\Delta\lambda}^{\lambda_1-\Delta\lambda} M(\lambda,T)\mathrm{d}\lambda$ and $\int_{\lambda_2-\Delta\lambda}^{\lambda_2-\Delta\lambda} M(\lambda,T)\mathrm{d}\lambda$ were radiation intensity targeted at magnesium alloy at temperature T, $\int_{\lambda_1-\Delta\lambda}^{\lambda_1+\Delta\lambda} M_O(\lambda,T)\mathrm{d}\lambda$ and $\int_{\lambda_2-\Delta\lambda}^{\lambda_2+\Delta\lambda} M_O(\lambda,T)\mathrm{d}\lambda$ were radiation intensity targeted at ideal blackbody at temperature T, $R(T)$ and $R_O(T)$ were ratio of two-band light current targeted at magnesium alloy and ideal blackbody respectively.

Due to oxidation and deformation in the process of heating magnesium alloy, emissivity ratio under its ignition temperature could not be directly measured, here we made the hypothesis (2): when measured magnesium alloy's temperature was very close to its ignition, namely, on the verge of igniting but with no sparks, emissivity ratio was a constant.

$R(T)$ and $R_O(T)$ at the same temperature should be measured separately: for one hand, current heating method was applied to heat magnesium alloy and output parameters of DC were adjusted, magnesium alloy's temperature was set to be close to its ignition but with no sparks, ignition temperature test system and C type thermocouple was employed to measure temperature, $R(T)$ could be determined by the former results, the functional block diagram was shown as Fig. 6.

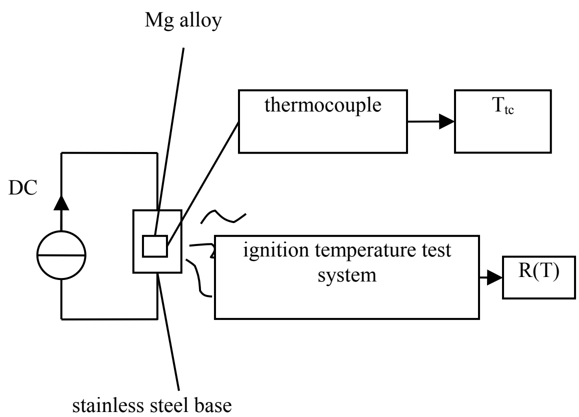

Fig. 6. Functional block diagram of acquiring $R(T)$ in emissivity ratio amendment test.

For the other hand, the temperature of medium temperature blackbody furnace was set to be T_{tc}, $R_O(T)$ could be obtained by results of ignition temperature test system, the corresponding functional block diagram was shown as Fig. 7. The measuring distance and angle must stay the same in both experiments.

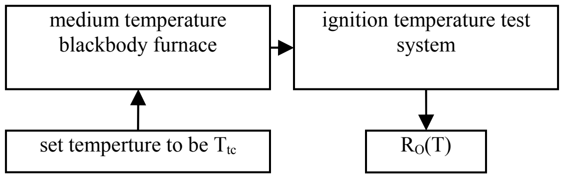

Fig. 7. Functional block diagram of acquiring $R_O(T)$ in emissivity ratio amendment test.

6.2. Data Processing and Analysis on Emissivity Ratio Amendment

Table 3 showed data results of emissivity ratio test. It could be seen that emissivity ratio grew as temperature grew, but the extent could be ignored, so this hypothesis could be verified. Finally emissivity ratio of AZ80 at its ignition temperature could be considered as 1.268.

Table 3. Data results of emissivity ratio test.

V_{tc}(mV)	T_{tc}(°C)	R(T)	Ro(T)	$\frac{\varepsilon_1}{\varepsilon_2}$
519.45	588.8	0.264	0.210	1.259
534.72	604.5	0.298	0.236	1.261
555.41	625.7	0.343	0.271	1.264
567.75	638.3	0.372	0.293	1.268

Two-color temperature T_C of Table 2 was amended on the basis of Table 3, it could be seen that test accuracy was enhanced greatly after amending and the relative error is 0.76 % in Table 4.

Table 4. Results of emissivity ratio amendment.

T_{OS}. (°C)	T_C. (°C)	T. (°C)	θ(%)
653.987	671.473	649.007	0.76

7. Conclusions

1) Material's emissivity test experiment was designed, current produced by high power supply was used to heat magnesium on the base, when magnesium alloy's temperature was very close to its ignition, C type thermocouple and OS4000 were employed to measure temperature, theoretical emissivity of AZ80 is 0.613.

2) Current heating method was applied to ignite AZ80, the relative error between ignition temperature test system's result and OS4000 result is 2.67 %;

3) Computational formula of emissivity ratio was inferred and relative test was carried out, theoretical emissivity ratio of AZ80 at its ignition temperature

is 1.268, temperature-measuring precision reaches 0.76 %.

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