SPECTROSCOPY OF HETEROPHASE PLASMA OF ELECTRIC ARC DISCHARGE BETWEEN W AND Mo ELECTRODES

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This paper deals with spectroscopy of plasma of electric arc discharge between tungsten and molybdenum electrodes. Spectrum of electric arc discharge between metal electrodes usually contains atomic lines of metals, which can be used for plasma diagnostics. In case of high-melting metals such as tungsten and molybdenum, not only line spectrum, but also continuous emission are observed. The attempts of simulation of such continuous emission and comparison with experimentallyobtained spectrum were performed.

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INTRODUCTION

Electric arc discharge between high melting materials as tungsten and molybdenum attracts scientific and practical interests. For example, tungsten cathodes are applicable in high-power thermal plasma torches (plasmatrons) [1], but usually only for non-oxidizing working gases or with special inert gas cathode protection. This circumstance explained by fast oxidation of hot tungsten and molybdenum with formation of relatively low-melting and even volatile oxides [2]. In the same time oxidation of tungsten and molybdenum can be used as advantage for fabrication of structured materials (oxides)and such oxidation can be performed in electric arc plasma source [3].

The aim of this work is investigation of spectra of plasma of electric arc discharge between tungsten and molybdenum electrodes, which contain strong continuous emission.

1. EXPERIMENT

The vertically oriented free-burning arc was ignited in air between the end surfaces of metallic tungsten or molybdenum non-cooled electrodes. The diameter of the rod electrodes was 6 mm, the discharge gap was 8 mm and DC current was 3.5 A.

The middle cross-section of electric arc discharge plasma was studied by optical emission spectroscopy technique [4]. The realized configuration of experimental setup with optical scheme on base of diffraction grating 600 g/mm permits simultaneous registration of spatial intensity distribution in spectral range 400…660 nm.

Spectrum of electric arc discharge between metal electrodes usually contains atomic lines of metals, which can be used for plasma diagnostics. But in case of high-melting metals as tungsten and molybdenum, not only linear spectrum, but continuous emission in background was also observed (Figs. 1, 2).

2. MODELING

Further diagnostics of plasma are complicated due to superposition of the continuous emission and line spectrum. For example, application of Boltzmann plots method for temperature measurement without considerationof this overlapping tends to unacceptable results. So, it is reasonable to study this continuous emission.

Continuous emission can be caused by different factors – thermal emission of heated bodies, recombination and bremsstrahlung continuum.

The bremsstrahlung emissioncaused by losing of kinetic energy of electrons due to Coulomb interaction with other charged particles, i.e. braking in electrostatic field. The bremsstrahlung,also known as free-free transactions, because particles don't change their free state during interaction and only change their energy by photon emission. The spectrum of bremsstrahlung continuum has flat form with exponential cut-off in short-wave range [5]. The emission coefficient of such continuum proportional to degree of ionization ($\leq 10^{-3}$ for arcs) and this type of spectra seems not typical for non-extremalelectric arcs.

Recombination continuum (free-bound transactions) differ from bremsstrahlung due to particles became bonded after interaction. As rule bremsstrahlung intensity dominate and only in short-wave part of spectrum recombination emission became important [5]. Therefore, recombination emission intensity is negligible in the arc spectrum, because it's intensity is lower than for bremsstrahlung.

In the same time injection of hot particles from electrodes into the arc volume is expected. Therefore, plasma can be considerate as hetero phase medium. For example, hot particles observed in plasma volume of electric arc discharge between composite Cu-W electrodes [6].

Thermal emission can be explained by radiationof hot matter injected in plasma volume by upward convective flows [3] or directly from electrodes' surface. In this assumption spectral brightness can be calculated according to Planck's law:

$$b_{Planck}(\lambda, T) = \frac{2hc^2}{\lambda^5}\left(\exp\left[\frac{hc}{\lambda k_B T}\right] - 1\right)^{-1},$$

where λ – wavelength; h and k_B – Planck and Boltzmann constants; c – speed of light; T – heated bodies temperature.

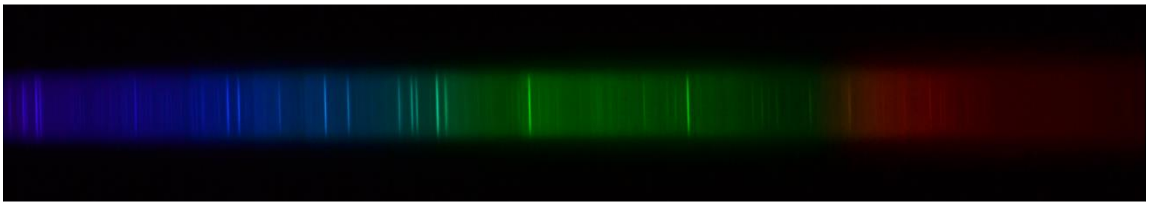


Fig. 1. Spectrum of electric arc between tungsten electrodes

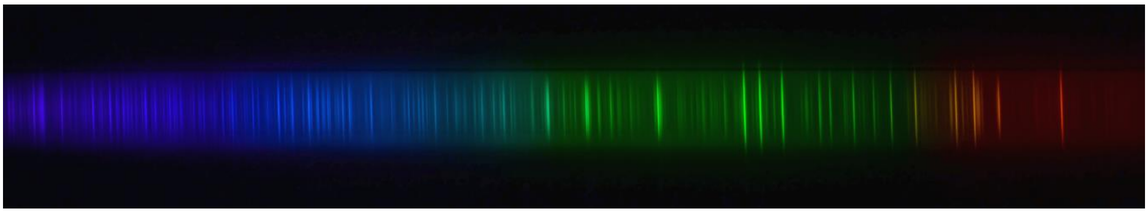


Fig. 2. Spectrum of electric arc between molybdenum electrodes

Sensitivity of spectral device can be obtained from registration of heated body with known temperature, for example tungsten ribbon lamp. So, spectral sensitivity $S(\lambda)$ was obtained previously. The observed brightness b_{obs} can be calculated with respect to spectral sensitivity:

$$b_{obs}(\lambda) = S(\lambda) \cdot b_{Planck}(\lambda, T) \cdot f,$$

where f – some adjusting factor from absolute scale to arbitrary units. It must be noted, that f is not strictly defined and must be selected carefully. In general, the task of superposition of calculated end experimental spectrum has solution in some f and T parameter space.

Intensity of simulated spectrum significantly rises whiletemperature T increasing, so appropriate decreasing of f is needed.

Simultaneous variation of T and f shows best coincidence of experimental and simulated spectrum at 4500…5500 K (Figs. 3, 4). If T < 4500 K simulated spectrum situated below experimental in short-wave range, while if T > 5500 K is situated above experimental spectrum.

Calculated in such way spectrum was compared with experimental spectrum (see Figs. 3, 4). So, continuous spectra can be treated by Planck formula and subtract for following study of spectra.

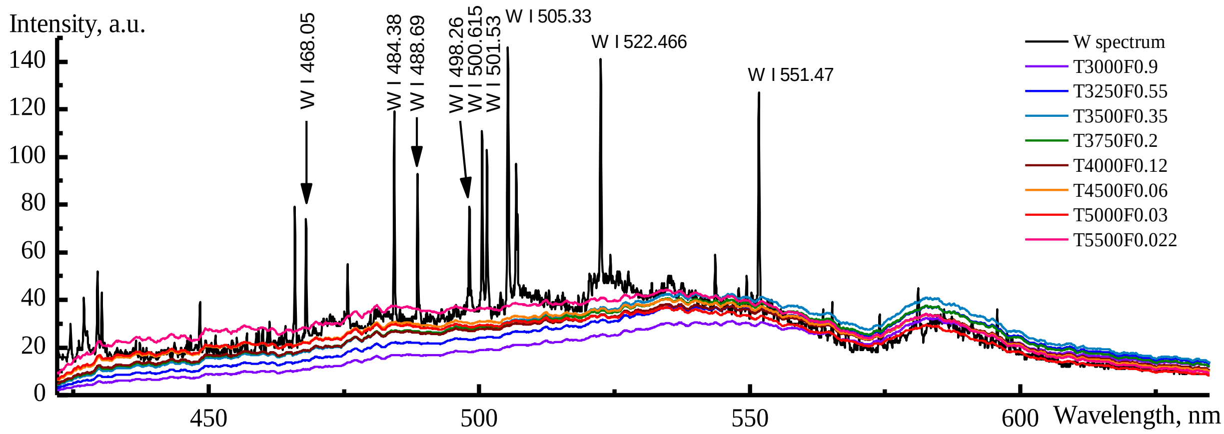


Fig. 3. Spectrum of electric arc discharge between tungsten electrodes and continuum simulation

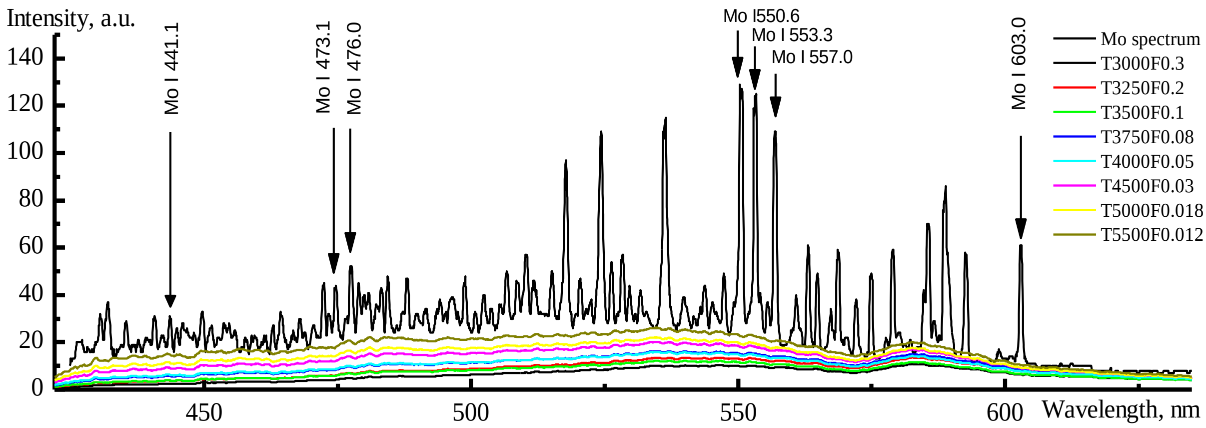
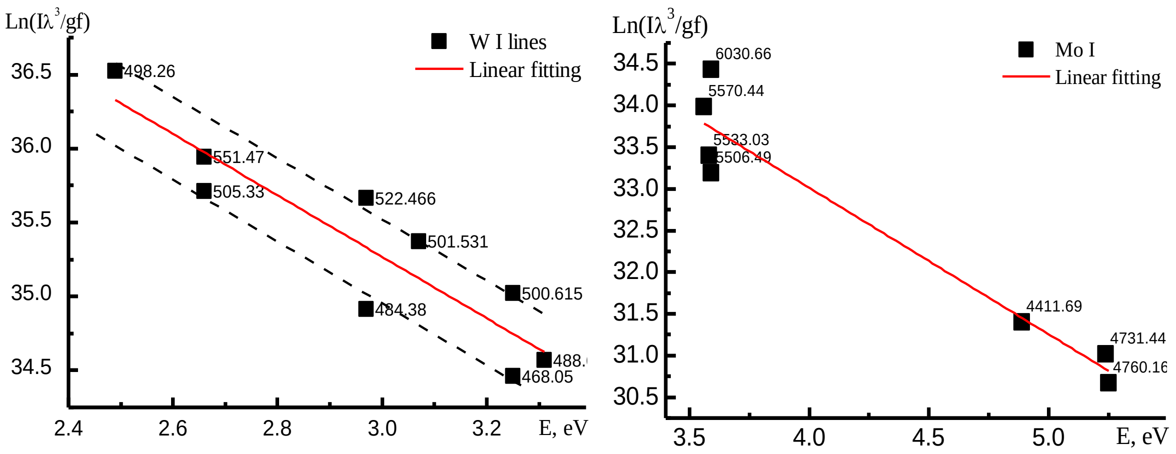


Fig. 4. Spectrum of electric arc discharge between molybdenum electrodes and continuum simulation



a b

Fig. 5. Boltzmann plots for arc plasma of electric arc discharge between tungsten (a) and molybdenum (b) electrodes

For further plasma diagnostics is necessary to subtract continuous emission from whole observed spectrum It can be performed in following way. Intensity of a spectral line *I* at certain spatial point*x*can be evaluated from spectral brightness distribution *b(λ)* as:

$$I\Big|_{\lambda,x} = \int_{-\Delta\lambda}^{+\Delta\lambda} b(\lambda)d\lambda,$$

where – Δ*λ* and +Δ*λ* some spectral range within spectral line profile. In case of digital image of spectra it is possible to substitute integration by summation:

$$I\Big|_{\lambda,x} = \sum_n b(n) ,$$

where n is pixel’s numbers belong to appropriate range from – Δ*λ* to +Δ*λ*.

Thereby, real line intensity without continuous spectra can be expressed

$$I_{real}\Big|_{\lambda,x} = \sum_n \left(b_{obs}(n) - b_{continuous}(n)\right) =$$

$$= \sum_n b_{obs}(n) - \sum_n b_{continuous}(n).$$

3. TEMPERATURE CALCULATION

This technique of continuum subtraction was performed for further plasma diagnostics, particularly for estimation of temperature by Boltzmann plots method. Applicable for diagnostics atomic spectral lines of W and Mo were selected previously [7]. Nine spectral lines for W (Fig. 5,a) and six spectrallines for Mo (Fig. 5,b) were used. The best satisfied simulated continuous spectra were subtracted.

The emission intensities along central axis of spectrum were used (see Figs.1, 2). The Abel inversion was not performed, so obtained results can be used only as temperature estimation. In the same time Abel inversion is not contradict with proposed method and will be performed in future studies.

The Boltzmann plot method is applicable when plasma is in local thermodynamic equilibrium (LTE), then the slopes of line, whichdrawn through the points corresponding to spectral lines, depends on plasma excitation temperature as:

$$s = 1/k_B T \rightarrow T = \left|1/k_B \cdot s\right|$$

where*s* – slope, k_B – Boltzmann constant.

Thereby, Boltzmann plots for plasma of electric arc discharges between tungsten (see Fig. 5,a) and molybdenum (see Fig. 5,b) electrodes with subtraction of continuous emission intensity allow us to estimate plasma excitation temperature. For tungsten the temperature is estimated as 5600 and about 6600 K for molybdenum.

CONCLUSIONS

Spectrum of electric arc between tungsten and molybdenum electrodes contains strong continuum in background, whichmust be taken into account during plasma diagnostics. Continuous emission can be caused by injection of electrodes material in arc volume, i.e. heterophase plasma has place. The mechanism of such injection must be defined by further investigation. Probably droplet transfer from electrode working surface has place. In the same time, some part of electrodes material can be transported into arc volume by upward convection flows.

Thesimulated according Planck’s law continuum shows reasonable agreement with real obtained spectra in 4500…5500 K temperature range. Thereby, it is possible to subtract continuum emission and properly define plasma temperature by spectral lines intensity.

Plasma temperature was estimated after subtraction of continuum emission by Boltzmann plot method. The temperature of plasma of electric arc discharge at 3.5 A between tungsten electrodes for central cross-section was estimated as 5600 K. In case of molybdenum electrodes, the temperature was estimated as 6600 K in the same conditions.

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СПЕКТРОСКОПИЯ ГЕТЕРОФАЗНОЙ ПЛАЗМЫ ЭЛЕКТРОДУГОВОГО РАЗРЯДА МЕЖДУ W- И Mo-ЭЛЕКТРОДАМИ

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Рассматриваются особенности спектроскопии плазмы электродугового разряда между вольфрамовыми или молибденовыми электродами. Спектр электрической дуги между металлическими электродами, как правило, содержит линии атомов металла. В случае тугоплавких металлов вольфрама и молибдена наблюдается не только линейчатый, но и непрерывный спектры. Предлагаются результаты моделирования такого непрерывного спектра и сравнение его с экспериментально зарегистрированным спектром.

СПЕКТРОСКОПІЯ ГЕТЕРОФАЗНОЇ ПЛАЗМИ ЕЛЕКТРОДУГОВОГО РОЗРЯДУ МІЖ W- ТА Mo- ЕЛЕКТРОДАМИ

А.В. Лебідь, А.М. Веклич

Розглядаються особливості спектроскопії плазми електродугового розряду між вольфрамовими або молібденовими електродами. Спектр електричної дуги між металевими електродами, як правило, містить лінії атомів металу. У випадку тугоплавких металів вольфраму та молібдену спостерігається не лише лінійчатий, але і неперервний спектри. Пропонуються результати моделювання такого неперервного спектра та його порівняння з експериментально зареєстрованим спектром.