Thermal stresses computation under high–current pulsed radiation of AISI M2 tool steel

A I Blesman\textsuperscript{1,2}, D V Postnikov\textsuperscript{1,2} and D A Polonyankin\textsuperscript{1,2}

\textsuperscript{1}Physics Department, Omsk State Technical University, 11 Mira Ave., Omsk, 644050, Russia
\textsuperscript{2}Scientific–educational Resource Center «Nanotechnology», Omsk State Technical University, 11 Mira Ave., Omsk, 644050, Russia

E–mail: nano@omgtu.ru

Abstract. Surface modification of metallic materials and alloys with concentrated energy flows (powerful electron beams and ion plasma flow, laser beams) has been widely used in various fields of manufacturing. The aim of physical and mechanical properties modification is to improve the performance of the critical parts fabricated from modified materials. The mentioned energy impacts give rise to radiation, thermal and mechanical effects causing the changes in morphology, microstructure, elemental and phase composition of the surface layers, which in turn may lead to hardness, wear corrosion resistance and red hardness increasing of modified materials. However, as experimental investigations are shown, in some cases irradiation promotes the crystal defects’ occurrence and often non-uniform heating leads to the cracks’ formation in the surface layers. Thus, selection of incident electrons energy, its current density and pulse duration, taking into account the thermal stress state, is an actual problem of modern radiation technologies. This paper provides a numerical solution of differential equations in partial derivatives for the temperature fields’ computation as well as radial and axial thermal stresses distribution in R6M5 (AISI M2) high-speed steel exposed to medium-energy (up to 400 keV) high–current (up to 1 kA/cm\textsuperscript{2}) pulsed (up to 1 µs) electron beam radiation. The obtained results can be useful in the optimal modes selection of tool steels and products at surface radiation treatment and evaluation of their service life.

1. Introduction

Methods of intense pulsed laser [1-3], ion [4-6] and electron beams [7-9] interaction with irradiated materials are widely used nowadays for surface modification of the metallic critical parts. These pulsed beam techniques allow high energy deposition at a short time within narrow depths near the material surfaces [7]. High–current pulsed electron beam (HCPEB) exhibits essential advantages over pulsed laser and ion beams by its versatile capabilities such as high efficiency, simplicity and reliability [7, 8]. Compared to the widely used laser, plasma, and ion beam treatments, HCPEB provides a narrow energy distribution, good surface finish and wide chosen energy density range [9]. It is more problem-free as compared to ion beam irradiation, which suffers from the impact of ionic impurities [10]. In contrast to ion beams, the application of electron beams allows the treatment of a significantly thicker surface layer [11].
2. Review of HCPEB application for materials modification

High current pulsed electron beams is a powerful method recently developed for surface processing of metallic materials applying for thermal protection, rapid annealing, surface cleaning and surface alloying [12, 13]. The classical applications of electron beam processing are welding, cutting and non-thermal hardening of metals and alloys [14]. HCPEB has been widely used to enhance the electric strength of vacuum insulation [15], to improve the electrochemical properties [13], i.e. antimicrobial properties of biocompatible materials [16], to increase mechanical and tribological properties of the metallic materials [17-20]. The pulsed electron irradiation is also used to improve the fatigue properties of titanium alloys [21], the wear and corrosion resistance of cutting tools made of high-speed steels and hard alloys [22-26], as well as technological properties can be tailored over a wide range by changing treatment parameters [27].

The pulsed electron irradiation induces a rapid heating and cooling of the surface together with the formation of thermal stress waves. As a result, improved surface properties, often unattainable with conventional surface treatment techniques, can be obtained fairly easily. This is particularly true for tribological and corrosion properties [7]. Yu. F. Ivanov et. al reported that modification of the structural properties of high-speed steel type S6-5-2 upon pulsed electron–beam quenching increases the wear resistance of cutting tools (drills) [28].

The temperature and stress fields are the main factors that determine the state and properties of the beam affected zone [20]. The HCPEB modified surface layer can be divided into three successive regions having different orders of magnitude of penetration depth in the material. In accordance with K Zhang et. al. classification there are three zones can be allocated: (i) a melted and rapidly solidified layer on the top surface (~1 µm), (ii) a heat affected zone where solid state phase transformation, deformation and recrystallization may occur (~10 µm) and (iii) a stress wave affected zone (~100 µm) where the microstructure or properties can be modified due to the stress wave propagation [8]. According to simple one-dimensional simulations of the temperature and the thermal stress fields (quasistatic, thermoelastic and shock stress) Y Qin et. al. noted that the generation of a stress wave is due to a special sublayer heating mode: the penetration of electrons in metals is much higher than photons and ions and the maximum energy deposition occurred at a sublayer depth [29]. Temperature–field simulation induced by HCPEB in the samples of stainless steel 316L and NiTi was carried out by solving the nonlinear non–stationary equation of heat conduction with allowance for the processes of melting and crystallization [24]. A three dimensional temperature prediction model of the electron beam irradiation was developed by J Kim et. al. [17]. An investigation was conducted primarily on temperature distributions on the material surface and heat penetration into the material depth to determine the melting zone during the large pulsed electron beam irradiation period. Investigation of heat conduction concerning the temperature and phase evolution induced by pulsed electron beam treatment of stainless steel (SS 316), aluminum (AlMg3), and copper (Cu) was carried out using experimental (time- and space-resolved schlieren imaging) and simulation (a Monte Carlo routine and a finite element method) approach [11]. By using X-ray diffraction technique K. M. Zhang et. al. conducted experimental examination of the quantitative evolution of the residual stress states in the surface layers of an AISI D2 steel subjected to the LEHCPEB treatment [30].

Although various studies have investigated experimental approaches and the effects of electron beam surface treatments, a numerical analysis to predict the processing results is still lacking, thus, more efforts should be devoted to improve model accuracy [17]. This paper provides the results of temperature fields’ calculation and thermal stresses simulation under high-current pulsed electron beam irradiation of AISI M2 tool steel. The developed approach could be useful for the optimal mode selection at irradiating the surfaces of parts with axial symmetry.

3. Algorithm of thermal stresses computation

To calculate the temperature fields, the absorbed dose of the electron beam is used as internal heat sources [31]. Computation of the absorbed dose is based on the Gaussian distribution. The temperature
distribution is calculated by using the heat conduction equation [32], taking into account phase transformations and nonuniform heat emission of internal sources through the depth of the sample with axial symmetry. Geometry of the sample is shown in figure 1a. Figure 1b presents the results of simulation the temperature distribution obtained by numerical methods. A sample of AISI M2 steel is subjected to a pulsed electron beam with an energy \( E = 400 \text{ keV} \) with a current density \( j = 0.6 \text{ kA/cm}^2 \) and a pulse duration \( t = 0.2 \text{ ms} \).

![Figure 1a. Geometry of the irradiated sample.](image1a.png)

![Figure 1b. Temperature distribution in relative coordinates \( z/z_{\max} \).](image1b.png)

The internal thermal stresses are calculated on the basis of the generalized Hooke’s law in cylindrical coordinates:

\[
\begin{align*}
\varepsilon_z &= \frac{1}{E} \left( \sigma_z - \mu \sigma_r - \mu \sigma_{\theta} \right) + \alpha T \\
\varepsilon_r &= \frac{1}{E} \left( \sigma_r - \mu \sigma_z - \mu \sigma_{\theta} \right) + \alpha T \\
\varepsilon_{\theta} &= \frac{1}{E} \left( \sigma_{\theta} - \mu \sigma_z - \mu \sigma_r \right) + \alpha T
\end{align*}
\]

(1)

Here \( \varepsilon_z, \varepsilon_r, \varepsilon_{\theta} \) are the relative deformations in a cylindrical coordinate system, \( \sigma_z, \sigma_r, \sigma_{\theta} \) are the corresponding stresses, \( \alpha \) is the linear expansion coefficient, \( \mu \) – Poisson’s ratio, \( E \) – elastic modulus, \( T \) – temperature.

The solution of the system (1) with respect to stresses allows obtaining expressions for their calculation:

\[
\begin{align*}
\sigma_z &= \frac{E}{1-\mu} \left[ \frac{1}{r^2} \int_0^r \! aTrdr + \frac{1}{r_{\max}^2} \int_0^{r_{\max}} \! aTrdr \right] \\
\sigma_r &= \frac{E}{1-\mu} \left[ \frac{2}{r_{\max}^2} \int_0^{r_{\max}} \! aTrdr - \alpha T \right] \\
\sigma_{\theta} &= \frac{E}{1-\mu} \left[ \frac{1}{r^2} \int_0^r \! aTrdr + \frac{1}{r_{\max}^2} \int_0^{r_{\max}} \! aTrdr - \alpha T \right]
\end{align*}
\]

(2)
4. Results and discussion
As calculations of the temperature distribution shown (for beam parameters mentioned above) the material of the sample was melted and cracked, which is confirmed by micrographs of the experimental sample after irradiation (figure 2a, figure 2b). Experimental analysis of the irradiated AISI M2 steel was carried out using a JEOL JCM–5700 microscope in a high vacuum mode. The signal type was secondary electrons (SEI). The Spot Size parameter was selected as 50, with the accelerating voltage value 20 kV and magnification from 500× to 1000×.

On the basis of the developed algorithm, an axial and radial stresses distribution through the sample’s depth of AISI M2 steel are calculated in a cylindrical coordinate system (for beam parameters mentioned above at the end of the pulse time) and presented in figure 3.

![Figure 2a. SEM micrograph of irradiated surface of AISI M2 steel, ×500.](image1)

![Figure 2b. SEM micrograph of irradiated surface of AISI M2 steel, ×1000.](image2)

![Figure 3. An axial and radial stresses distribution ($\sigma_z$, $\sigma_r$) in relative coordinate ($z/z_{max}$) at surface irradiation by electron beam with an energy $E=400$ keV with a current density $j=0.6$ kA/cm$^2$ and a pulse duration 0.2 ms (at the end of the pulse time).](image3)

The presented axial and radial stresses’ dependencies from the relative coordinate ($z/z_{max}$) show that the maximum stress arise in the radial direction $\sigma_r$ with the largest value on the surface. For working out the optimal radiation modes the calculation of temperature fields and stresses was carried out while reducing the beam current density that allows avoiding a cracks’ grid formation. As the results of calculations show, estimated stresses do not exceed the tensile strength of AISI M2 steel (3.25 GPa) at pulse duration $t=0.2$ μs and $E=400$ keV while the current density takes on value $j=0.12$ kA/cm$^2$. 
5. Conclusion
Algorithm of thermal stresses computation is proposed for estimation the temperature fields and corresponding axial and radial stresses at irradiating the surfaces of parts with axial symmetry.

On the basis of obtained theoretical and experimental results it could be concluded that a high-current pulsed electron beam with energy $E=400$ keV, current density $j=0.6$ kA/cm$^2$ and pulse duration $t=0.2$ μs melts and cracks AISI M2 steel. The temperature gradients formed by irradiation lead to the occurrence of thermal stresses in axial and radial directions exceeding the tensile strength of material that caused a fine grid of cracks formation. By thermal stresses simulation it was established the electron beam parameters ($E=400$ keV, $j=0.12$ kA/cm$^2$, $t=0.2$ μs) for the AISI M2 steel radiation treatment.

Acknowledgments
This work was supported by the Omsk State Technical University [grant number 18041B].

References
[1] Lawrence J, Ocelík V and De Hosson J T M 2018 Adv. Laser Mater. Process. 15 413
[2] Akamatsu H and Yatsuzuka M 2003 Surf. Coat. Technol. 169–170 219
[3] Yu Z, Yang G, Zhang W and Hu J 2018 J. Mater. Process. Technol. 255 129
[4] Xiaoyun L, Sha Y, Weijiang Z, Baoxi H, Yugang W and Jianming X 2000 Surf. Coat. Technol. 128–129 381
[5] Yu X, Shen J, Qu M, Zhong H, Zhang J, Zhang Y, Yan S, Zhang G, Zhang X and Le X 2015 Nucl. Instrum. Methods Phys. Res., Sect. B 365 225
[6] Yu X, Huang W, Shen J, Zhang J, Zhong H, Cui X, Liang G, Zhang X, Zhang G, Yan S, Remnev G E and Le X 2017 Nucl. Instrum. Methods Phys. Res., Sect. B 409 338
[7] Grosdidier T, Zou J X, Bolle B, Hao S Z and Dong C 2010 J. Alloys Compd. 504 508
[8] Zhang K, Ma J, Zou J and Liu Y 2017 J. Alloys Compd. 707 178
[9] Gao Y 2013 J. Alloys Compd. 572 180
[10] Zhang C, Gao Q, Lv P, Cai J, Peng C–T, Jin Y, and Guan Q 2018 Powder Technol. 325 340
[11] An W, Krasik Y E, Fetzer R, Bazylev B, Mueller G, Weisenburger A and Bernshtam V 2011 J. Appl. Phys. 110 093304
[12] Qin Y, Zou J, Dong C, Wang X, Wu A, Liu Y, Hao S and Guan Q 2004 Nucl. Instrum. Methods Phys. Res., Sect. B 225 544
[13] Proskurovsky D I, Rotshtein V P, Ozur G E, Ivanov Y F and Markov A B 2000 Surf. Coat. Technol. 125 49
[14] Arkhipov A V and Sominski G G 2001 Tech. Phys. 46 1106
[15] Rotshtein V P 2004 Surf. Coat. Technol. 180–181 382
[16] Fetzer R, Mueller G, An W and Weisenburger A 2014 Surf. Coat. Technol. 258 549
[17] Kim J, Lee W J and Park H W 2018 Appl. Therm. Eng. 128 151
[18] Xia H, Zhang C, Lv P, Cai J., Jin Y and Guan Q 2018 Nucl. Instrum. Methods Phys. Res., Sect. B 416 9
[19] Xu H, Hu J, Ma C, Chai L and Guo N 2017 Mater. Trans. 58 1519
[20] Zou J, Qin Y, Dong C, Wang X, Wu A and Hao S 2004 J. Vac. Sci. Technol., A 22545
[21] Ozur G E, Proskurovsky D I, Rotshtein V P and Markov A B 2003 Laser Part. Beams 21 157
[22] Zhao H and Wang X H 2012 Adv. Mater. Res. 557–559 1954
[23] Samih Y, Marcos G, Stein N, Allain N, Fleury E, Dong C and Grosdidier T 2014 Surf. Coat. Technol. 259 737
[24] Shepel’ D A and Markov A B 2017 Tech. Phys. Lett. 43 139
[25] Zou J X, Zhang K M, Hao S Z, Dong C and Grosdidier T 2010 Thin Solid Films 519 1404
[26] Lou C, Zhang L, Lu X, Lyu X, Jin G and Wang Q 2017 J. Mater. Eng. Perform. 26 5864
[27] Panin A V, Kazachenok M S, Borodovitsina O M, Sinyakova E A, Ivanov Y F and Leontieva–Smirnova M V 2014 AIP Conf. Proc. 1623 467
[28] Ivanov Y, Matz W, Rotshtein V, Günzel R and Shevchenko N 2002 Surf. Coat. Technol. 150 188
[29] Qin Y, Dong C, Song Z, Hao S, Me X, Li J, Wang X, Zou J and Grosdidier T 2009 J. Vac. Sci. Technol., A 27 430
[30] Zhang K M, Zou J X, Bolle B and Grosdidier T 2013 Vacuum 87 60
[31] Tkachenko E A, Postnikov D V, Logachev I A, Logacheva A I, Blesman A I and Polonyankin D A 2016 Proc. Eng. 152 589
[31] Blesman A I, Postnikov D V, Tkachenko E A and Polonyankin D A 2017 IOP Conf. Ser.: Mater. Sci. Eng. 168 012050