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The Effect of Laser Shock Peening on the Thermophysical Parameters of Metals

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Abstract

Using Ti64 titanium alloy as an example, the article discusses the change in the thermophysical parameters of metals under the influence of a hardening method such as laser shock peening the essence of which is the formation of residual compressive stresses in the material under the influence of high-intensity laser radiation. The experiments are carried out with plates made of Ti64 titanium alloy, which is one of the most common construction materials in modern industry. One of the plates is a control specimen, and the surface of the second one is subjected to laser processing. The thermophysical parameters of specimens are determined using the infrared thermography method, the advantage of which is the ability to simultaneously measure two coefficients, thermal diffusivity and thermal conductivity of an explored material. The specimen is heated by the laser for some time, which can be perceived as a point heat source on the surface of the plate. Simultaneously with the laser action, the surface temperature of the specimen is recorded by an infrared camera. The thermophysical coefficients are determined as optimization parameters when matching experimental data with the analytical solution of the heat equation for a geometry similar to the experimental setup.

Keywords: Laser shock peening; Residual stress; Infrared thermography; Laser flash method; Thermophysical parameters

1. INTRODUCTION

Knowledge of the mechanical, strength and thermal properties of metallic materials is a prerequisite for the trouble-free operation of structures and mechanisms under real conditions. The urgent task of our time is to increase the service life and hardening of metal parts and components by various methods. The most common of these are surface shot blasting, rolling, equal-channel angular pressing, laser peening [1–5], etc. In addition to these traditional methods of surface treatment methods, laser shock peening (LSP) has a number of advantages: the absence of global thermal effects, ability to locally treat parts with complex geometry [6–9], short processing time, lower surface roughness [10], deeper residual stresses [11]. Moreover, LSP can precisely control the pulsed laser energy to achieve desirable strengthening effects in specific regions, particularly small fillets and notches that are inaccessible to shot peening [12,13]. This makes the LSP economically and practically competitive. The essence of the technology is the formation of the residual stress (RS) field in the surface layer of the material by laser shock impact. The spatial configuration of the RS field, the magnitude of the maximum compressive RS and the depth of the layer, in which the compressive RS are formed play a significant role in the nucleation of defects and the development of material damage. The optimum LSP mode (i.e., the optimum combination of tensile and compressive RS) allows the strength and fatigue properties of the material to be improved. The laser impact treatment produces a layer with a modified microstructure [14], resulting in plastic deformation. Plastic deformation induces distortion of crystal lattice, producing a large number of different defects. It leads to the changes in the physical properties such

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as thermal conductivity and specific heat capacity [15,16]. In Ref. [17] it has been shown that the thermal conductivity of copper bars is reduced under the influence of the plastic deformation. In Ref. [18], using molecular dynamics, it was found that the thermal conductivity of insulating solids is reduced by the application of uniform pressure. As is mentioned in Ref. [19], steady-state methods are usually used to directly determine the thermal conductivity with a high accuracy. At the same time, accurate determination of the specific heat capacity is performed by calorimetric techniques based on its definition. However, these methods impose severe limitations on the specimen geometry and require complex experimental setups due to sensitivity to heat losses and temperature sensor uncertainties [20,21]. In this sense, the flash method [22–25] is the most optimal, having a sufficiently high precision and allowing the identification of some thermal properties. It is generally used to determine only the thermal diffusivity, but if the parameters of the heat source are known, it also allows the measurement of the volumetric heat capacity [19].

In this work, infrared thermography (IRT) is used to implement a flash method and to define the thermodynamic properties of the material after LSP. The aim of this work is to determine the influence of laser-shock treatment on the thermal properties and heat release of titanium alloy Ti64 during quasistatic tension of flat specimens using IRT.

2. EXPERIMENTAL PROCEDURE

Let us consider a point heat source on the surface of a homogeneous isotropic flat specimen of thickness l. The solution of the thermal conductivity equation for a point located on the side of the sample opposite to the source has the form [19]:

$$T(t)=\frac{q}{4\lambda l}\left[\ln\left(\frac{4\alpha}{\omega^2}t+1\right)+2\sum_{n=1}^{+\infty}(-1)^n\exp\left(\frac{\pi^2n^2\omega^2}{4l^2}\right)\right.$$
$$\left.\times\left(\Gamma\left[0,\frac{\pi^2n^2\omega^2}{4l^2}\right]-\Gamma\left[0,\frac{\pi^2n^2(4\alpha t+\omega^2)}{4l^2}\right]\right)\right], \qquad (1)$$

where q is a heat flux capacity, ω is the distance at which the heat flux capacity is reduced by the factor of $1/e$, α and λ are the coefficients of thermal diffusivity and thermal conductivity, respectively, and $\Gamma(x)=\int_0^{+\infty}t^{x-1}e^{-t}dt$ is the upper incomplete gamma function. The parameters of the heat source q, ω or the thermophysical parameters α, λ can be determined simultaneously from one measurement.

The thermophysical properties of the specimens are measured using a setup schematically shown in Figure 1. A continuous laser with high power illuminates a flat specimen 3 mm thick from one side for some time, playing the role of a point heat source. Infrared shooting is carried out on the other side of the specimen with a FLIR SC5000 camera with a spatial resolution of 10^{-4} m and a spectral sensitivity of 25 mK. The camera is calibrated based on standard calibration tables. The shooting frequency is 100 frames per second.

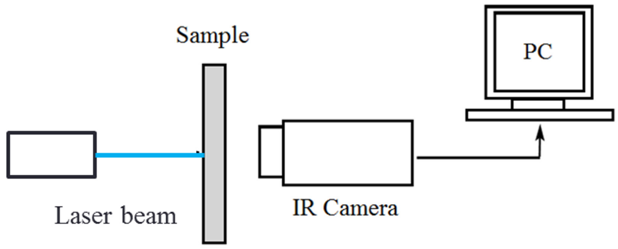

Fig. 1. Scheme of the experiment.

A typical view of a heated specimen at one of the moments of heating and typical temporal dependence of temperature in the most heated point are shown in Figures 2a and 2b, respectively. It can be noted that the shape of the heated area is close to circular, which indicates a high uniformity of heating along the azimuth and indicates the closeness of the laboratory setting to the mathematical model of a point source on the plate surface.

The experiments use a plate made of non-rusting steel (AISI 304 with well-known thermal conductivity and thermal diffusivity $\lambda = 16.2$ W/m·K and $\alpha = 4.15\cdot10^{-6}$ m²/s,

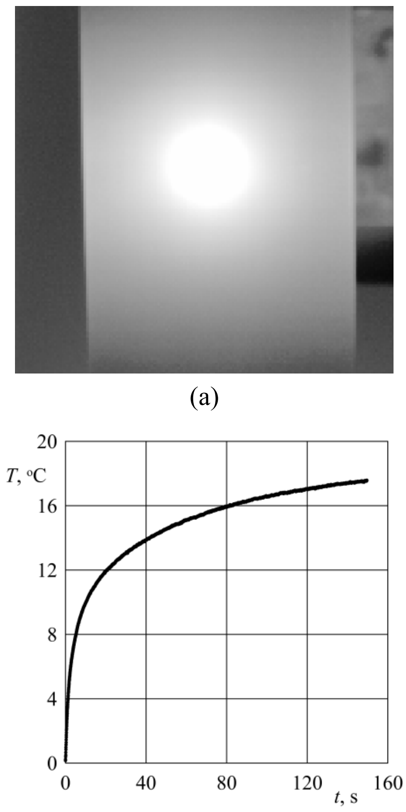

Fig. 2. (a) IR camera frame, typical view of a heated area. (b) Typical view of the temperature data in the central point.

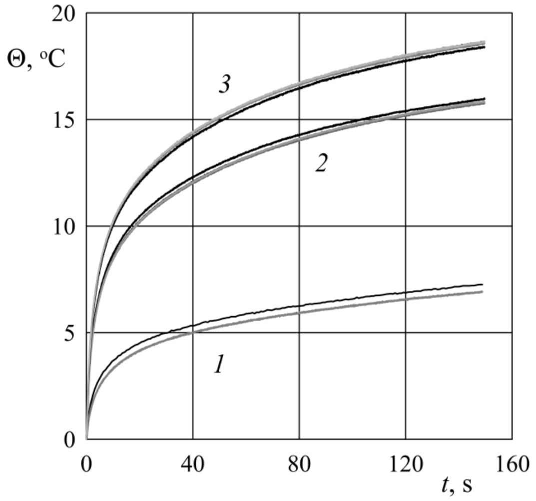

Fig. 3. Temperature data for experiments with different materials: *1* – AISI 304, *2* – Ti64, *3* – Ti64 processed.

respectively) and two specimens of Ti64 titanium alloy, one of which is processed using the LSP method, and the second one is not. The experiments with a steel specimen make it possible to use known coefficients to calculate the parameters of the heat source, which, in turn, are necessary to calculate the thermophysical properties of titanium samples.

To determine the thermal diffusivity and the thermal conductivity we solve the problem of best fitting the experimental results to the curve, which is the theoretical solution (1). The optimization parameters are α and λ.

3. RESULTS AND DISCUSSION

The temporal temperature growth with respect to the temperature of the first frame for different samples is shown in Figure 3. Experiments with each specimen are carried out five times, the agreement of the experimental curves obtained for one material indicates a good reproducibility of the results. The instability of the temperature growth on the graph does not exceed the point size. It can also be seen that the temperature growth for the LSP processed Ti64 specimen is significantly more intense than that for the unprocessed one in all the experimental series. Let us recall that experiments with a steel specimen are carried out to identify the parameters q and ω of the heat source.

Figure 4 shows the results of the optimization problem solution for each material. In order not to clutter the graphs, the fits are given for only one experiment in each series. It can be seen that in the considered area the mismatch of the theoretical and experimental curves is small and qualitatively does not exceed 0.2 °C. The main error in the measurement of the thermophysical properties appears as a result of a slight mismatch of the experimental curves in one series.

The parameters of the heat source obtained in experiments with AISI 304 are $\omega = (3.8 \pm 0.3) \times 10^{-3}$ m and $q = 0.31 \pm 0.01$ W. Corresponding values of thermal conductivity and diffusivity for the untreated specimen are $\lambda = 7.8 \pm 0.2$ W/m·K and $\alpha = (7.2 \pm 0.6) \times 10^{-6}$ m^2/s. The optimization for the LSP processed specimen shows a decrease in $\lambda = 6.7 \pm 0.2$ W/m·K and an increase in $\alpha = (7.9 \pm 0.5) \times 10^{-6}$ m^2/s, although, taking into account the error, the values of thermal diffusivity can be perceived as coinciding.

It is important to note that the similar influence of plastic deformation on the thermophysical properties of metal had been earlier observed in Ref. [19], where the parameters of AISI 304 at different levels of deformation were measured with the same method.

4. CONCLUSION

The experimental research of the influence of the LSP treatment on the thermophysical properties of metal was carries out. The coefficients of thermal conductivity and thermal diffusivity for Ti64 titanium alloy were measured using the method based on infrared thermography with following data processing.

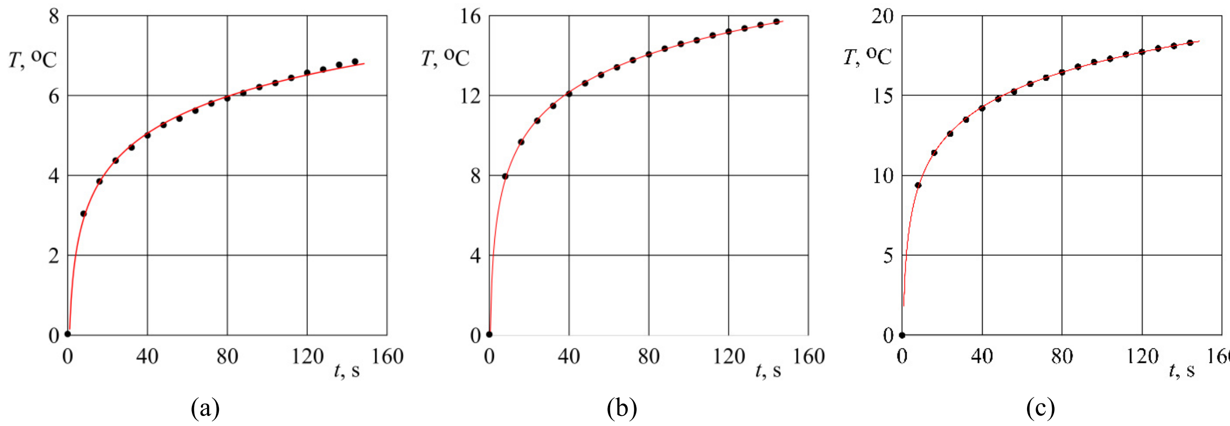

Fig. 4. Comparison of the experimental points (black, every two hundredth point is shown) with theoretical solution (red line): (a) AISI 304, (b) Ti64, (c) Ti64 processed.

It was found that the laser processing reduces the coefficient of thermal conductivity while the thermal diffusivity increases, which coincides with the dependencies of thermophysical properties on the value of elastic deformations identified earlier.

The clarification of the physical mechanisms leading to the changes in thermophysical parameters is the task of future research.

ACKNOWLEDGMENTS

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REFERENCES

[1] Z. Qin, B. Li, R. Chen, H. Zhang, H. Xue, C. Yao, L. Tan, *Effect of shot peening on high cycle and very high cycle fatigue properties of Ni-based superalloys*, International Journal of Fatigue, 2023, vol. 168, art. no. 107429.

[2] O.M. Ikumapayi, E.T. Akinlabi, P. Onu, O.P. Abolusoro, *Rolling operation in metal forming: Process and principles – A brief study*, Materials Today: Proceedings, 2020, vol. 26, no. 2, pp. 1644–1649.

[3] M. Nagaraj, D. Ravi Kumar, K.S. Suresh, S. Neelakantan, *Effect of equal channel angular pressing on the microstructure and tribocorrosion characteristics of 316L stainless steel*, Vacuum, 2023, vol. 210, art. no. 111908.

[4] S. Prithivirajan, G.M. Naik, S. Narendranath, V. Desai, *Recent progress in equal channel angular pressing of magnesium alloys starting from Segal's idea to advancements till date – A review*, International Journal of Lightweight Materials and Manufacture, 2023, vol. 6, no. 1, pp. 82–107.

[5] H. Soyama, C. Kuji, Y. Liao, *Comparison of the effects of submerged laser peening, cavitation peening and shot peening on the improvement of the fatigue strength of magnesium alloy AZ31*, Journal of Magnesium and Alloys, 2023, vol. 115, no. 5, pp. 1592–1607.

[6] S. Mannava, A.E. Mcdaniel, W.D. Cowie, H. Halila, J.E. Rhoda, J.E. Gutknecht, *Laser shock peened gas turbine engine fan blade edges*, US Patent, 1997, patent no. US5591009.

[7] S. Mannava, A.E. Mcdaniel, W.D. Cowie, *Laser shock peened rotor components for turbomachinery*, US Patent, 1996, patent no. US5492447.

[8] S.J. Ferrigno, K.G. Mcallister, S. Mannava, *Laser shock peened gas turbine engine seal teeth*, US Patent, 2001, patent no. US6200689.

[9] D.A. Casarcia, W.D. Cowie, S. Mannava, *Laser shock peened bearings*, US Patent, 1996, patent no. US5584586.

[10] A.G. Sanchez, C. You, M. Leering, D. Glaser, D. Furfari, M.E. Fitzpatrick, J. Wharton, P.A.S. Reed, *Effects of laser shock peening on the mechanisms of fatigue short crack initiation and propagation of AA7075-T651*, International Journal of Fatigue, 2021, vol. 143, art. no. 106025.

[11] B.K. Pant, A.H.V. Pavan, R.V. Prakash, M. Kamaraj, *Effect of laser peening and shot peening on fatigue striations during FCGR study of Ti6Al4V*, International Journal of Fatigue, 2016, vol. 93, part 1, pp. 38–50.

[12] X. Zhang, Y. Ma, M. Yang, C. Zhou, N. Fu, W. Huang, Z. Wang, *A comprehensive review of fatigue behavior of laser shock peened metallic materials*, Theoretical and Applied Fracture Mechanics, 2022, vol. 122, art. no. 103642.

[13] J.M. Yang, Y.C. Her, N. Han, A. Clauer, *Laser shock peening on fatigue behavior of 2024–T3 Al alloy with fastener holes and stopholes*, Materials Science and Engineering A, 2001, vol. 298, no. 1–2, pp. 296–299.

[14] S. Mironov, M. Ozerov, A. Kalinenko, N. Stepanov, O. Plekhov, R. Sikhamov, V. Ventzke, N. Kashaev, G. Salishchev, L. Semiatin, S. Zherebtsov, *On the relationship between microstructure and residual stress in laser-shock-peened Ti-6Al-4V*, Journal of Alloys and Compounds, 2022, vol. 900, art. no. 163383.

[15] V. Rodionov, A. Goncharov, *Effect of plastic deformation on the electrical resistivity of metals*, Combustion, Explosion and Shock Waves, 1995, vol. 31, no. 3, pp. 313–318.

[16] C. Çetinarslan, *Effect of cold plastic deformation on electrical conductivity of various materials*, Materials & Design, 2009, vol. 30, no. 3, pp. 671–673.

[17] A. Williams, *Effect of cold work on the thermal conductivity of copper*, Journal of Mechanical Engineering Science, 1965, vol. 7, no. 3, pp. 335–338.

[18] S. Bhowmick, V. Shenoy, Effect of strain on the thermal conductivity of solids, The Journal of Chemical Physics, 2006, vol. 125, no. 16, art. no. 164513.

[19] M. Zhelnin, A. Iziumova, A. Vshivkov, O. Plekhov, *Experimental study of an effect of plastic deformation on thermal properties of stainless steel*, Quantitative InfraRed Thermography Journal, 2019, vol. 16, no. 1, pp. 74–86.

[20] D. Kraemer, G. Chen, *A simple differential steady-state method to measure the thermal conductivity of solid bulk materials with high accuracy*, Review of Scientific Instruments, 2014, vol. 85, no. 2, art. no. 025108.

[21] P. Haines, *Principles of thermal analysis and calorimetry*, The Royal Society of Chemistry, Cambridge, 2002.

[22] B. Abad, D. Borca-Tasciuc, M. Martin-Gonzalez, *Non-contact methods for thermal properties measurement*, Renewable and Sustainable Energy Reviews, 2017, vol. 76, pp. 1348–1370.

[23] T. Lian, A. Kondo, M. Akoshima, H. Abe, T. Ohmura, W. Tuan, M. Naito, *Rapid thermal conductivity measurement of porous thermal insulation material by laser flash method*, Advanced Powder Technology, 2016, vol. 27, no. 3, pp. 882–885.

[24] H. Dong, B. Zheng, F. Chen, *Infrared sequence transformation technique for in situ measurement of thermal diffusivity and monitoring of thermal diffusion*, Infrared Physics & Technology, 2015, vol. 73, pp. 130–140.

[25] N. Pech-May, M. Arantza, S. Agustin, *Simultaneous measurement of the in-plane and indepth thermal diffusivity of solids using pulsed infrared thermography with focused illumination*, NDT & E International, 2016, vol. 77, pp. 28–34.

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Влияние лазерной ударной проковки на теплофизические параметры металлов

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Аннотация. В статье на примере титанового сплава ВТ6 обсуждается изменение теплофизических параметров веществ под действием такого метода упрочнения поверхности, как лазерная ударная проковка (ЛУП), суть которого заключается в формировании на поверхности материала остаточных сжимающих напряжений под влиянием лазерного излучения высокой интенсивности. Эксперименты проводятся с пластинами из титанового сплава ВТ6, который является одним из наиболее распространенных композиционных материалов в современной промышленности. Одна из пластин представляет собой контрольный образец, а поверхность второй подвергнута лазерной обработке. Теплофизические параметры образцов определяются с помощью метода инфракрасной термографии (ИКТ), преимущество которого заключается в возможности одновременного измерения двух коэффициентов, например, температуропроводности и теплопроводности. Поверхность образца нагревается лазером в течение некоторого времени, что можно воспринимать, как точечный источник тепла на поверхности пластины. Одновременно с действием лазера температура поверхности образца фиксируется инфракрасной камерой. Теплофизические коэффициенты определяются как параметры оптимизации при согласовании экспериментальных данных с аналитическим решением уравнения теплопроводности для геометрии аналогичной постановке эксперимента.

Ключевые слова: лазерная ударная проковка; остаточное напряжение; инфракрасная термография; метод лазерной вспышки; теплофизические параметры