Proceedings of "Applications of Physics in Mechanical and Material Engineering" (APMME 2024)

Physical Phenomena Occurring During Laser Remelting of the Surface Layer of Tool Steel

A. Dziwis*, M. Bonek, W. Pakieła, A. Śliwa and W. Mikołejko

Division of Materials Processing Technology and Computer Techniques in Materials Science, Institute of Engineering Materials and Biomaterials, Silesian University of Technology, Konarskiego St. 18a, 44-100 Gliwice, Poland

Doi: 10.12693/APhysPolA.147.196 *e-mail: amadeusz.dziwis@polsl.pl

The undertaken simulation using finite element method concerned the calculation of heat propagation during laser processing in various process variants, considering the power of the laser beam and the technique of delivering powder to the melting zone. The proposed model was based on the nonlinear thermal conductivity change, specific heat and density depending on temperature. The heat supply to the processing site was assumed to be a heat beam corresponding to a laser power of 1.4, 1.7, and 2.1 kW. The latent heat effects are considered in the solidification analysis. The melting point consists of the same material as the substrate and no chemical reaction occurs there. The properties of the simulated materials and their surface condition depend on the absorbency. The focus was on the physical phenomena occurring during laser remelting of the surface layer of tool steel.

topics: physical properties, engine piston, modelling, Ansys computer simulation

1. Introduction

The finite element method (FEM) is a numerical technique used to solve differential equations and engineering or physical problems that are difficult or impossible to solve analytically. FEM is particularly useful for analysing systems with complex geometries, materials with varying properties, and time-dependent loads. It has wide applications in fields such as mechanics, electrical engineering, thermodynamics, and structural analysis. FEM is widely used in the analysis and optimization of laser surface treatment processes. FEM enables precise modelling and simulation of the temperature distribution, stresses, and deformations in the material during laser processing, allowing for accurate prediction of treatment outcomes. In processes such as laser hardening, cladding, or microstructure modification, FEM facilitates the optimization of process parameters such as laser power, exposure time, and scanning speed to achieve the desired mechanical and microstructural properties of the material. Additionally, this method helps to minimize the risk of undesirable defects, such as cracks or excessive stresses, leading to improved treatment efficiency and quality. The finite element method has become one of the most powerful tools in engineering and applied sciences, enabling effective analysis of highly complex problems. Workflow in FEM/CAE (CAE — Computer-Aided Engineering) is divided into three parts:

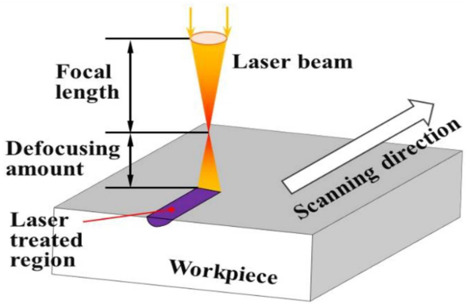

Fig. 1. Process of laser surface treatment [11].

- Preprocessing phase — define and divide the problem domain into finite elements by discretizing it into nodes and elements. Choose a shape function to approximate the physical behaviour of each element, ensuring that it represents the continuous behaviour of the element. Derive equations for each individual element. Combine the elements to represent the entire problem by constructing the global stiffness matrix. Include boundary conditions, initial conditions, and applied loads [1–5].

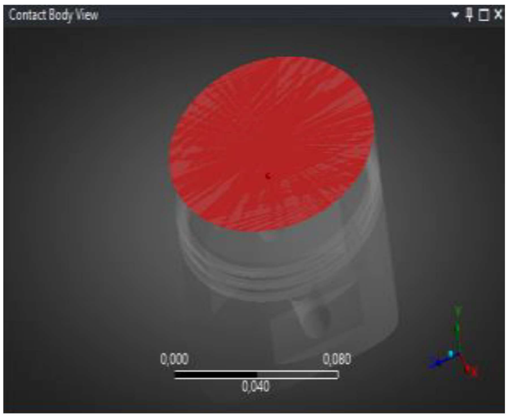

Fig. 2. Prepared surface.

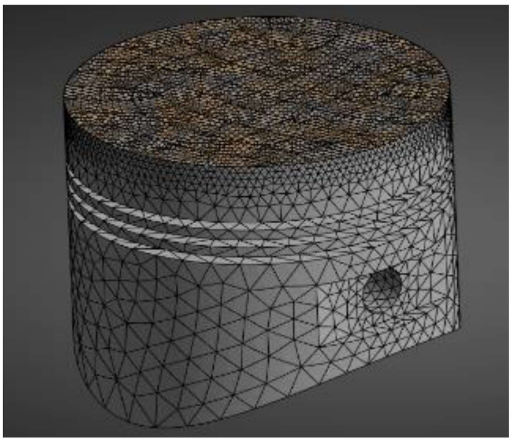

Fig. 3. Prepared mesh.

TABLE I

Material properties.

Parameter	Unit	M10 Tool Steel	Ti–6Al–4V
density	g/cm^3	7.85	4.43
tensile strength	MPa	800–1100	950–1100
elastic modulus	GPa	210	114
thermal conductivity	W/(m K)	20–25	6.7
thermal expansion coefficient	10^{-6}/K	11.5	8.6
hardness (hardened)	HRC	60–65	35

- Solution phase — simultaneously solve the resulting system of linear or nonlinear algebraic equations to determine nodal values such as displacements or temperatures at specific nodes.
- Postprocessing phase — extract additional relevant results such as principal stresses, heat fluxes, or other derived quantities of interest.

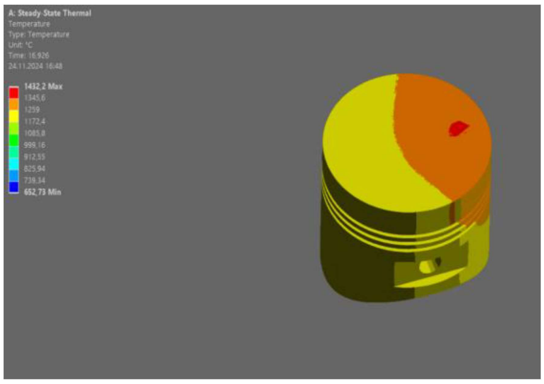

Fig. 4. Temperature distribution results for the 1.4 kV laser with the highest temperature at the laser point, i.e., 1432.2°C.

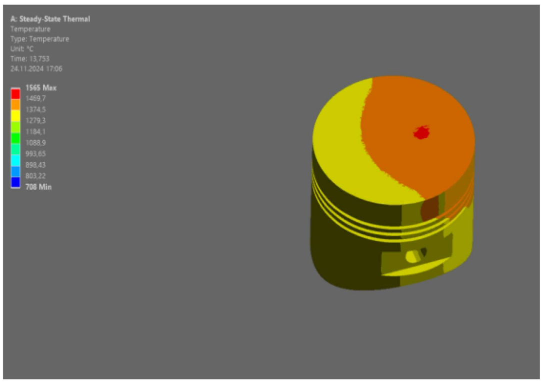

Fig. 5. Temperature distribution results for 1.7 kV laser with the highest temperature at the laser point, i.e., 1565°C.

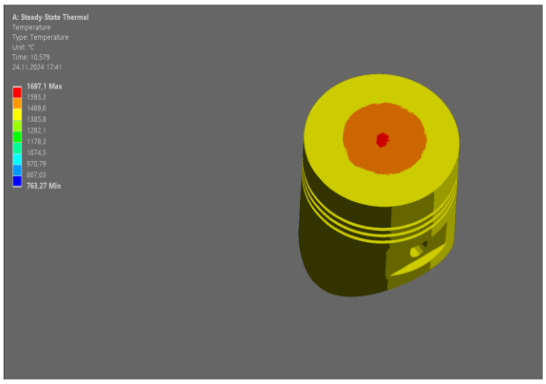

Fig. 6. Temperature distribution result for 2.1 kV laser with the highest temperature at the laser point, i.e., 1697.1°C.

Laser surface treatment is an advanced engineering technique that utilizes concentrated laser light to modify the surface of materials in order to improve their physical and mechanical properties. By precisely controlling the energy, duration, and location of the laser's action, it is possible to achieve

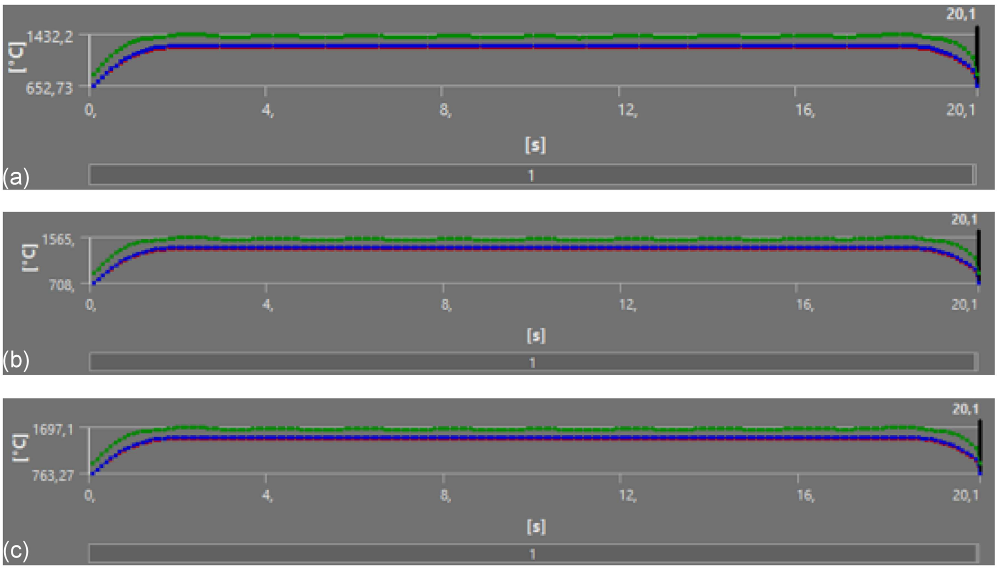

Fig. 7. (a) Average temperature distribution result for the smallest laser power. (b) Average temperature distribution result for the medium laser power. (c) Average temperature distribution result for the highest laser power.

TABLE II

The stress results for individual models.

Power	1.4 kW	1.7 kW	2.1 kW
σ	737.38 MPa	811.60 MPa	883.02 MPa

desired effects such as increased hardness, corrosion resistance, wear resistance, and other material characteristics such as high-temperature endurance. Laser surface treatment is an umbrella term for several processes in which laser energy interacts with a material to induce localized changes in its surface structure. These processes are highly precise and allow for selective modification of the material's surface, which is critical in many industrial fields [6–8].

This method is primarily used to improve mechanical properties such as hardness or wear resistance, but also to modify the microstructure of the material, influencing its performance and durability. The most commonly applied types of laser surface treatment include hardening, cladding, ablation, and microstructure modification [9–11] (see Fig. 1).

2. Material and method

The model was prepared in SolidWorks and imported into Ansys Workbench. The next step was to implement the material on the surface of the main object (Fig. 2). Then, the path of the laser beam through the given surface was prepared, the finite element mesh was created (Fig. 3), and the given boundary conditions were calculated. Three analyses were prepared with different laser powers. Fixed parameters were assumed for the calculations, such as the beam displacement rate of 5 mm/s and the laser diameter of 5 mm. Two materials were used for the analyses — M10 tool steel and Ti–6Al–4V superalloy material. Table I lists the material data used in the computer simulation.

After receiving the result from computer analyses, we use

$$\sigma = E\,\alpha\,\Delta T \tag{1}$$

to calculate the stresses in the model. In (1), σ is the thermal stress (in Pa, MPa), E — Young's modulus (modulus of elasticity of the material) (in Pa or MPa), α — coefficient of thermal expansion of the material (in 1/K), ΔT — temperature difference (in K or °C).

3. Results

The results obtained from numerical calculations made it possible to determine the effect of laser power on the temperature not only on the laser operating surface, but also on the entire component. Figures 4–6 show the results from the analysis of the laser transition over the surface and the temperature distribution in the model. In Fig. 4, the results for the laser with the smallest given power are presented, in Fig. 5 — for the laser with medium power, and in Fig. 6 — for the laser with the largest power. The graphs in panels a–c of Fig. 7 show the temperature result in the model, where the line in the middle of the graph shows the average result (in degrees Celsius) of the laser transition over time. Table II shows the stress distribution results for each model at different laser powers of 1.4, 1.7, and 2.1 kW.

4. Conclusions

The results showed that the use of the laser beam caused a significant and rapid increase in temperature at the point of incidence. This caused intensive changes in the structure of the processed material, but due to the precise area of the laser beam, these changes were limited only to the immediate area. This shows one of the greatest advantages of using laser surface treatment, i.e., obtaining a changed layer only in the indicated places, minimizing the heat-affected zone and eliminating the need for additional processes such as stress relief or annealing. Animations of the process clearly showed the area of heat influence, which decreases on the processed surface the closer the beam is to the center of the piston head, and the larger the closer to the edge. The simulations showed that increasing the laser power by approximately 0.3 kW increased the temperature by approximately 120 and 130°C, respectively, thereby increasing the stress in the generated coating by approximately 60 MPa.

References

[1] Z. Li, F. Meng, H. Ding, W. Wang, Q Liu, *Materials* **12**, 2835 (2019).

[2] B. Yelamanchi, E. MacDonald, N.G. Gonzalez-Canche, J.G. Carrillo, P. Cortes, *Materials* **13**, 5264 (2020).

[3] A.M. Rocha, A.I. Machado, T. Almeida, J. Vieira, M. Facão, *Sensors* **20**, 6409 (2020).

[4] K. Chadha, Y. Tian, J.G. Spray, C. Aranas Jr., *Arch. Metall. Mater.* **69**, 783 (2024).

[5] R.S. Yadav, V. Yadava, *J. Manuf. Process.* **27**, 241 (2017).

[6] Y. Lee, H. Sah, *J. Mater. Sci.* **51**, 6257 (2016).

[7] H.-W. Liu, T.-C. Chang, J.-Y. Tsai et al., *Appl. Phys. Lett.* **108**, 173504 (2016).

[8] D.R. Corradi, A.Q. Bracarense, B. Wu, D. Cuiuri, Z. Pan, H. Li, *J. Mater. Process. Technol.* **283**, 116723 (2020).

[9] C.G. Ozoegwu, *Int. J. Machine Tools Manuf.* **79**, 24 (2014).

[10] Y. Kawasuji, Y. Adachi, K. Moro, K. Kakizaki, M. Washio, *J. Laser Micro/Nanoeng.* **17**, 133 (2022).

[11] J. Wu, C. Zhang, P. Jiang, C. Li, H. Cao, *Green Manuf. Open* **1**, 3 (2023).