Analytical investigation on temperature distribution of high-strength bolt during CW-laser surface treatment

Kyushu University Student Member ○Qidi WANG Kyushu University Fellow Member Shigenobu KAINUMA
TOYOKOH Inc. Non-member Peng HUO

1. Introductions The continue-wave Laser (CW-Laser) beam can remove impurities, coating, and corrosion products on the metal surface, it has been widely used in the surface cleaning of metals and structures engineering. Existing studies have shown that CW-Laser irradiation on the surface of steel plate can reach temperatures as high as 1500°C in the range of 100μm depth on the surface[1)], which may cause the high-strength bolt connections to fail because of the materials properties decrease. Therefore, temperature distribution analysis is required, to ensure safety of the bolted connection components during laser surface treatment. In this study, we used the finite element solid model of the bolt and compared the temperature measured value from the thermocouple of the laser irradiation specimens, which obtained a good match. Furthermore, through the FE model, the temperature range of each bolt position under different irradiation durations was analyzed, which provides a reference for CW-Laser bolt surface treatment.

2. Test Methods To obtain the temperature change of the bolts during the laser irradiation, design the bolts with a thermocouple. Considering the working temperature range, embedded the thermocouple at the position about 20mm deep on the non-irradiated side of the bolt. The tested F10T M22 high-strength bolt and a friction connection specimen were selected, as shown in Fig.1. A total of six specimens including 12 bolts were tested: two specimens for irradiation at the bolt head, while other four for the nut.

Laser treatment was performed in the environment temperature about 30°C. The treatment was carried out using the CW-Laser rotated by a prism as a spinning 3kW laser ring, irradiating the steel surface with the ring moving by hand transmitter. The diameter of the laser spot is 430 μm, and the rotating prism refracts the laser beam at a speed of 5000 rad/s, so that the laser spot irradiates the steel surface in a circular ring path, and the diameter of the ring is 26 cm. The distance between the transmitter and the irradiated surface was about 210mm. The laser ring rotated clockwise around the bolt or nut during the irradiation, with every 20s as an irradiation duration unit. After irradiation, the specimen cools down in the indoor environment to 35°C and finishes the data counting. The bolt temperature change was recorded every 20s during the entire irradiation process through the datalogger.

The solid model of the bolt–nut connection was constructed using the FEM code MSC.Marc/Mentat has meshed with a length of 5mm, as Fig.2(a) shows. Directly constraint both sides of the model steel plate. The bolt/nut's surface heat flow was applied to the bolt/nut to simulate the laser beam irradiation process. Considering the energy consumption and loss, set the input power as 1.5kW, which is 50% of the output energy of the laser transmitter. The contact relationship of all components was defined as direct contact. Since all parts of the specimen were made of carbon steel, the elastic modulus E, thermal expansion coefficient α, specific heat C, thermal conductivity λ, and thermal convection heat transfer coefficient h were set the same[2)], and their changes with temperature were listed in Table 1.

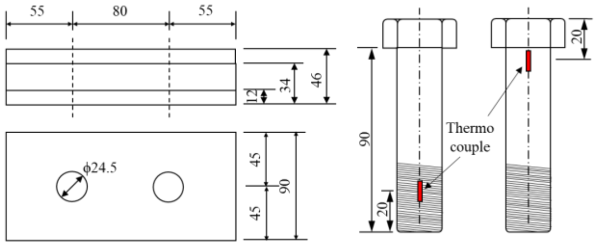
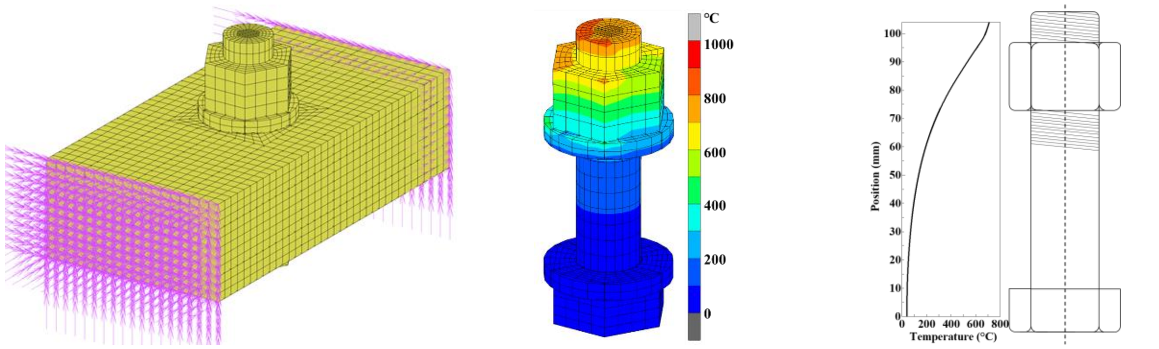


Fig.1 Friction connection specimen and high strength bolt

Table 1 Materials properties of carbon steel

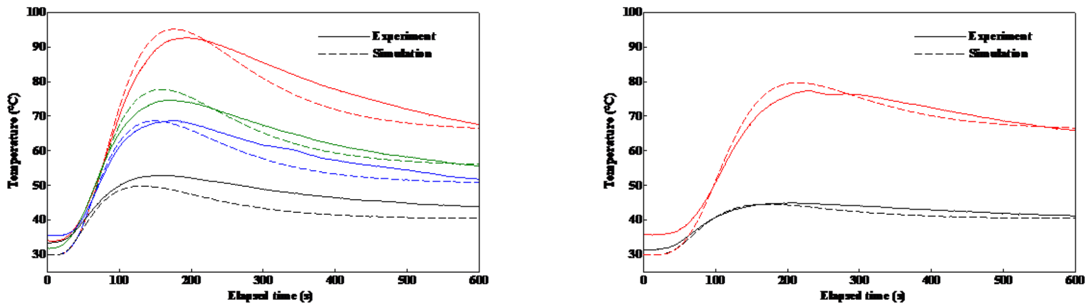
Temperature (°C)	E (GPa)	α, (10^{-6}/°C)	C (kJ/(kg·°C))	λ (W/(m·°C))	h(W/(m^2·°C))
25	206	14.6	0.462	45	25
300	193	11.3	0.560	41	500
500	170	11.8	0.652	38	3400
800	86	17.8	1.297	32	11000
1000	34	19.6	0.604	30	18000
1300	30	19.6	0.604	30	33000
1500	30	19.6	0.604	30	45000

Keywords: Laser surface treatment, Finite-element analysis , High-strength bolt , Temperature analysis
Contact address: 744 Motooka , Nishi-ku, Fukuoka, 819-0395, Japan, Tel: +81-092-802-3392



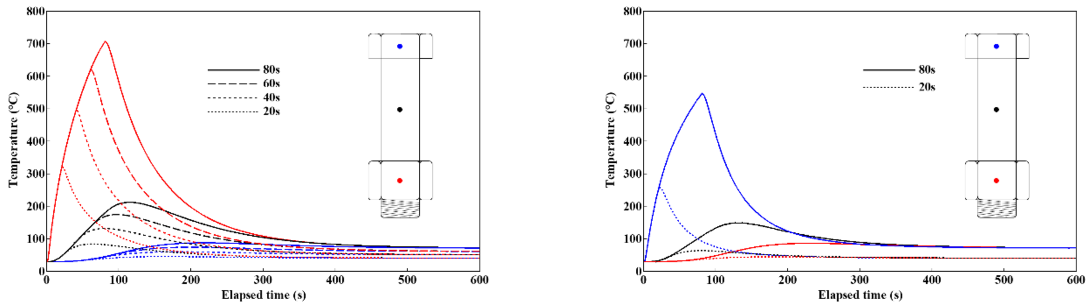
(a) Mesh and boundary condition (b) Temperature field cloud (c) Temperature Distribution

Fig.2 FE model of the bolt–nut connection



(a) Contrast of nut side laser irradiate (b) Contrast of bolt side laser irradiate

Fig.3 Time-dependence of temperature of bolt and nut



(c) Average temperature when irradiating on nut (d) Average temperature when irradiating on bolt

Fig.4 Average temperature during irradiating

3. Test Results Time-dependence of temperature of bolt and nut is shown in Fig.3, the comparison between numerical simulation and the experiment of bolt temperature shows the same trend and value in the same position of the bolt. Therefore, it can be considered that the solid FE model can correctly show the temperature distribution of each position of the bolt during laser surface treatment.

From Fig.4(a) and (b), the temperature of the irradiated area changes very sharply, reaching the average temperature of about 300°C with only 20s of continuous irradiation. During irradiation on the nut side, the bolt temperature was higher than irradiation on the bolt side, caused by the direct irradiation on the screw. During the irradiation process, the high temperature at the nut may cause the bolt to fail directly. Pang, X.P. and Guo, Z. have shown that when carbon steel temperature reaches 300°C, its strength starts to decrease[3,4]. The strength at 600°C was only half of that at room temperature. So it was not recommended to continuously irradiate high-strength bolts for more than 40s to ensure safety during processing.

4. Summary & Findings Continuous irradiation on the nut side will cause an unsafe temperature on the nut area. It is recommended that a single irradiation duration does not more than 40s to ensure safety in case of Continuous irradiation of 3kW with spinning laser ring.

References 1) Zhuang, S., Kainuma, S., Yang, M., Haraguchi, M., Asano, T.: Investigation on the peak temperature and surface defects on the carbon steel treated by rotating CW laser. Optics & Laser Technology. 135, 106727 (2021).; 2) Xing, Y., Wang, W., Al-azzani, H.: Assessment of thermal properties of various types of high-strength steels at elevated temperatures. Fire Safety Journal. 122, 103348 (2021).; 3) Pang, X.-P., Hu, Y., Tang, S.-L., Xiang, Z., Wu, G., Xu, T., Wang, X.-Q.: Physical properties of high-strength bolt materials at elevated temperatures. Results in Physics. 13, (2019). 4) Guo, Z., Lu, N., Zhu, F., Gao, R.: Effect of preloading in high-strength bolts on bolted-connections exposed to fire. Fire Safety Journal. 90, (2017).

