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Multi-objective optimization in surface transformation hardening of S50C carbon steel by single-mode fiber laser

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KEYWORDS

Grey relational analysis,
Laser material processing,
Surface hardening,
Austenization temperature
Hardened zone

ABSTRACT

Laser transformation hardening (LTH) process has become a better alternative for manufacturing industries. LTH offers a non-contact method, creating a pristine manufacturing setting and yielding high-quality products efficiently and cost-effectively at a significant scale. In the present work, parametric optimization for laser transformation hardening of JIS S50C medium carbon steel experimentally investigated. The grey relational analysis (GRA) was utilized by considering multiperformance characteristics, namely austenitizing temperature, and hardened depth. The GRA results confirmed that the best combination of process parameters was obtained during laser power 150 W, scanning speed 15 mm/s, and track distance 100 μm. Scanning speed was found to be the process parameter that provides the most significant effect compared to laser power and track distance in obtaining higher austenitizing temperature and greater hardened depth through the response table. The study revealed the multi-performance characteristics can be enhanced by selecting the proper process parameters.

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1.0 INTRODUCTION

Laser utilization within the manufacturing industry has been more common in the past years. The usage of lasers for surface treatment has also gain more popularity, which includes processes such as laser cleaning and transformation hardening (Nath & Sarkar, 2018). Through transformation hardening, the surface treated can have enhanced mechanical properties that are beneficial depending on the needs of the industry. Laser transformation hardening (LTH) process has been firstly introduced in the automotive industry to perform surface hardening of gear housing in 1973 (Muthukumaran & Babu, 2021). The LTH process of steel requires the specimen to be irradiated to its Ac3 austenization temperature. The temperature is held over time to allow phase transition from ferrite to austenite to occur. This follows with rapid self-quenching by the bulk of the material transforming the phase again to martensite. The finished specimen has a micro-hardened layer that consists of martensite phase of steel as shown in Figure 1. Since the process does not require any external quenchant, LTH process provides an advantage over other conventional hardening processes such as induction hardening and flame hardening (Babu et al., 2011).

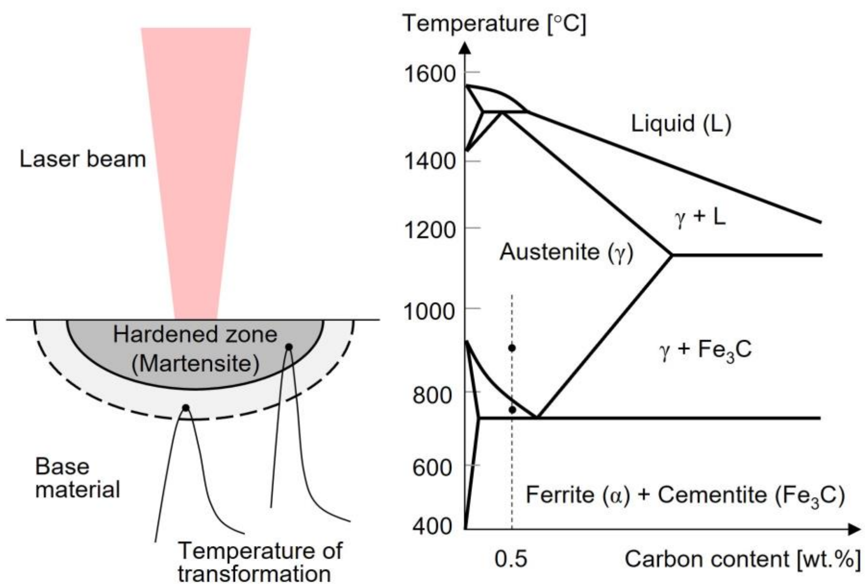

Figure 1: Principle of LTH thermal cycle at two points in 0.5% C steel and shape of hardened zone cross-section.

The introduction and use of newer and technology in the last few years, for example the use of a high-speed optical scanner, more commonly known as a Galvano scanner, has increase the potential of LTH process to be viable in the present and the future. High-speed optical scanners were used by researchers for large area transformation hardening increasing the versatility of the process by attaching the scanner to a CNC router (Martínez et al., 2012). Wide area scanning using scanning optics have been researched to understand the thermal effects of different hardening parameters on the hardening performance by investigating the temperature regimes during the irradiation process (Martínez et al., 2017). The research conducted utilized a laser connected to scanner, attached to a CNC router to irradiate samples at different speeds and power.

Hardening parameters were found to affect the total energy levels with scanning speeds being the most relevant parameters affecting the LTH process.

Cordovilla et al. (2021) created a two-step procedure to the LTH process for specific austenization requirements of Cr-Mo steels. They highlighted the main problem of LTH process were predicting the hardening parameters to achieve requirements of hardening performance, because of the non-linear relationship of the hardening parameters to the hardening performance. They also attempted to solve this problem by first conducting a numerical analysis of the irradiance distribution and the resulting hardening profile. Followed by creating a simulation by using Equivalent Laser Power Density Distribution (ELPDD) and real tests to transform irradiance distribution into hardening parameters. The non-linear nature of the relationship of the hardening parameters and the hardening performance were further discussed by Lakhkar et al. (2008) and Mioković et al. (2004). Since martensite formation is dependent on the irradiated material reaching the critical Ac3 temperature generating austenite, the accurate predictions are difficult to obtain due to the high heating and cooling rates. The researchers attempted to solve this problem through a microstructural analysis and a volume control procedure respectively.

Grey relational analysis (GRA) is a method for solving multi-objective optimization problems. Past researches for engineering and laser materials processing had successfully utilized GRA to solve multi-objective optimization problems by quantifying complex multiple objectives into a single value called the grey relational grade (Mutalib et al., 2020; Tamrin et al., 2014). Tamrin et al. (2014) carried out an experiment to optimize parameters for laser joining of dissimilar materials. While Pu et al. (2021) used GRA incorporated with the Taguchi method for laser assisted machining of Si_3N_4. Both researches, calculated the grey relational grade to rank parameters used that gives the best performance characteristics (i.e., responses).

In the present work, a parametric optimization of LTH process on JIS S50C medium carbon steel was experimentally investigated. Hardening performance characteristics consisted of austenizing temperature, and hardened depth were analysed to attain the optimum hardening parameters using GRA.

2.0 EXPERIMENTAL WORKS

Figure 2 shows the schematic diagram of experimental setup for the LTH process. The LTH process was conducted using a single-mode fiber laser (SPI: SP-200C) with a wavelength of 1070nm and maximum peak power of 200W. The laser source was connected to a Galvano scanner via fiber optic and an f-theta lens was used to ensure the focal point plane was perpendicular to the focusing lens. Specimens were irradiated at a defocused distance of 20 mm and argon gas was used as a shielding gas to limit oxidation from occurring. As the process increases the temperature of the metal significantly, argon gas was used to provide shielding and prevent the steel from reacting with air (Dinesh Babu et al., 2013). The defocused distance of 20 mm was used to reduce the melting effects during irradiation. The typical power density range for transformation hardening process are between 10^4 to 10^5 W/cm^2 (Martínez et al., 2017). The power density of the laser at the focal plane is in the range of 10^6 to 10^7 W/cm^2, due to the beam diameter being 18 μm. By defocusing the beam by 20 mm from the focal plane the beam diameter was increased to 130 μm, subsequently the power density was decreased to a suitable working range of approximately 10^4 to 10^5 W/cm^2. The laser power and scanning speed were controlled from a computer through the software Marking Mate. A pyrometer was used to measure temperature at a specific location on the specimen during irradiation and temperature data from the pyrometer readings was recorded. The laser was set to continuous wave (CW) mode during the LTH process.

The specimen used for the experiment was JIS S50C medium carbon steel with the chemical composition as shown in Table 1. The specimen has a length, width, and depth of 30 mm, 30 mm and 10mm (thickness), respectively. Irradiation area was set through the Marking Mate software with the dimensions of 30 mm length and 6 mm width as shown in Figure 2. The LTH process was conducted with the LTH parameters that consisted of laser power, scanning speed and track distance. While the output responses were austenization temperature and hardened depth. All the LTH parameters were selected to have three levels, and a full factorial experiment design of experiment (DOE) was implemented. Table 2 shows the details of the LTH parameters and their levels.

The 90W level for the power parameter was chosen to test the effect of sub-100W laser power irradiation. The level 150 W was chosen instead of the maximum output power of 200W to not excessively burden the laser to operate at its maximum power, which can cause significant reduction in the lifespan of the laser source. Power of 120W was chosen as the mid-point in between the maximum selected power level of 150W and the minimum selected level of 90W. The levels for the scanning speed were selected to ensure enough irradiation time for the transformation hardening to take place. The lowest speed of 15mm/s was selected to ensure that each track was irradiated for 2 seconds, due to the width of the specimen being 30mm. Increments of 10mm/s were then used to investigate the effect of increasing scanning speed on the specimen at the levels 25mm/s and 35mm/s. Track distance was selected to be at minimum of 60μm for the lowest level allowing the irradiation area to accommodate 100 scanned tracks. A reduction of 40 tracks were than selected for the subsequent levels of 60 tracks and 20 tracks to increase the track distance levels to 100μm and 300μm respectively.

After the LTH process, the samples were cut perpendicular to the scanning direction and polished. The samples were etched using a 2% nital chemical solution to visualise the hardened zone. The hardened depth for each sample was measured using digital microscope.

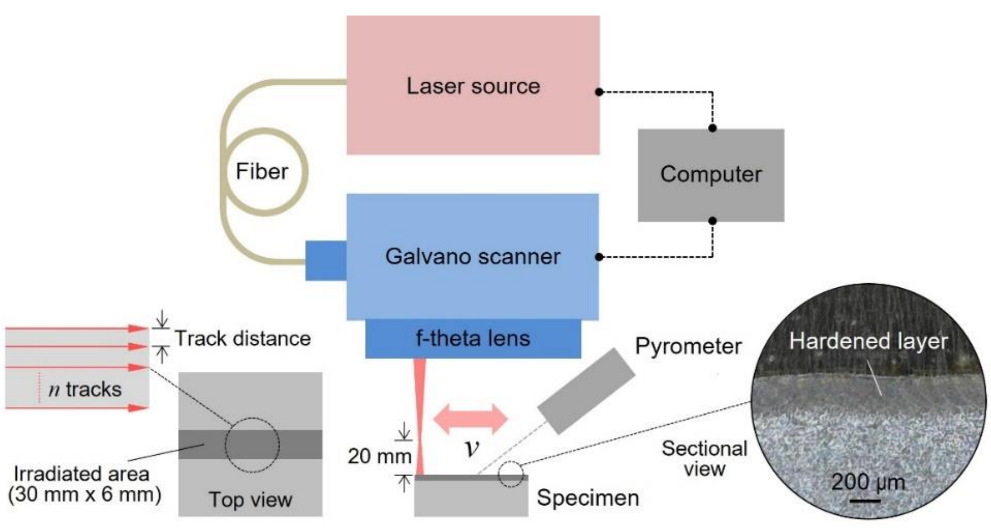

Figure 2: Schematic diagram of experimental setup.

Table 1: Chemical composition of JIS S50C medium carbon steel.

C	Mn	P	S	Si	Fe
0.47-0.53%	0.6-0.9%	0.03%	0.035%	0.15-0.35%	Balance

Table 2: LTH parameters and their levels.

Parameter	Levels
Laser power, P (W)	90, 120, 150
Scanning speed, v (mm/s)	15, 25, 35
Track distance, d (μm)	60, 100, 300

3.0 GREY RELATIONAL ANALYSIS

Grey relational analysis (GRA) was used to analyse the data obtained. The methodology which includes equations for conducting GRA was adopted from (Mutalib et al., 2020). The performance criteria consisted of austenization temperature (T), and hardened depth (HD) were first normalized. Since austenization temperature and hardened depth were to be maximized, the following equation (1) was used to normalize the values.

$$x_i^*(k) = \frac{x_i(k) - x_{i\,min}(k)}{x_{i\,max}(k) - x_{i\,min}(k)} \tag{1}$$

where $x_i^*(k)$ and $x_i(k)$ are the normalized sequence and the observed sequence respectively, with k^{th} response of i^{th} specimen.

Grey relational coefficient (GRC) for each response was then calculated from the normalized data. The GRC, $\xi_i(k)$ represents the relationship between the ideal response and the experimental data was calculated using equation (2).

$$\xi_i(k) = \frac{\Delta_{min} - \zeta\Delta_{max}}{\Delta_i(k) + \zeta\Delta_{max}} \tag{2}$$

where $\Delta_i(k)$ was the deviation sequence between the reference and comparability sequence $x_0^*(k)$ and $x_j^*(k)$ respectively. As shown in equation (3), Δ_i is the absolute value of the difference between $x_0^*(k)$ and $x_j^*(k)$. While Δ_{min} and Δ_{max} were the minimum and maximum value of Δ_i respectively, as shown in equation (4) and (5). The distinguishing coefficient, ζ (where, $\zeta \in [0,1]$) was used with the value of 0.5 that is used by researchers in general (Mahmoudi et al., 2020).

$$\Delta_i = \left| x_0^*(k) - x_j^* \right| \tag{3}$$

$$\Delta_{min} = min_{(\forall j \in i)} min_{(\forall k)} \left| x_0^*(k) - x_j^* \right| \tag{4}$$

$$\Delta_{max} = max_{(\forall j \in i)} max_{(\forall k)} \left| x_0^*(k) - x_j^* \right| \tag{5}$$

The following equation (6) was then used to calculate the grey relational grade (GRG), γ_i. Equation (6) averages the GRC of each response by *n*. In this case *n* was equal to 2 corresponding to the responses of austenizing temperature and hardened depth. The higher value of the GRG could give a higher ranking, since a higher value indicates the experimental value is closer to the ideal normalized value.

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n} \xi_i\,(k) \tag{6}$$

4.0 RESULTS AND DISCUSSION

Figure 3 shows the hardened depth and maximum austenization temperature under different scanning speeds of 15, 25 and 35 mm/s with constant 120 W laser power and 100 μm track distance. It can be observed that the lower scanning speed significantly generates a deeper hardened depth, which is attributed to the higher hardening temperature employed during LTH process. Table 3 lists the recorded austenization temperature (T), and hardened depth (HD) with each corresponding hardening parameter used for LTH process. Both T and HD are mean values from three replication experiments for each condition. The data shows that for specimens 16, 19, 22, 25, 26 and 27, the hardening parameters are insufficient for hardening to occur. The hardness did not increase from its base hardness indicating the hardening process did not occur. Thus, hardened depths for these specimens were assigned the value of zero.

Table 4 consists of the normalized values of the responses after equation (1) is used. Both T and HD are to be maximized in this optimization problem. The GRC for each performance characteristic are calculated using equation (2) followed by the calculations for the GRG using equation (6). Subsequently the responses are ranked according to the GRG. Based on the ranking in Table 4 the first ranked response is experiment number 6 with the parameter value of 150 W, 15 mm/s and 100 μm for laser power, scanning speed and track distance, respectively. Experiment number 6 with a GRG value of 0.867 indicated the deviation from the idealized value of 1 is the lowest. Figure 4 further illustrates the GRG value of each specimen to visualize the ranks of different parameter combinations to its performance characteristics.

A response table was created as in Table 5 to show the effects of the parameters on the performance characteristics. Average GRG from the associated parameter and level is calculated and the difference, called delta (δ) between the maximum and minimum values is calculated. The parameters are then ranked according to the values of delta. A large value of δ signifies the degree of effect the parameter has on the process, a larger value of δ shows that the process is sensitive to different levels of the parameter. Thus, the significance of each parameter can be determined through examining the value of δ, which indicated that the scanning speed is the most significant parameter in the LTH process.

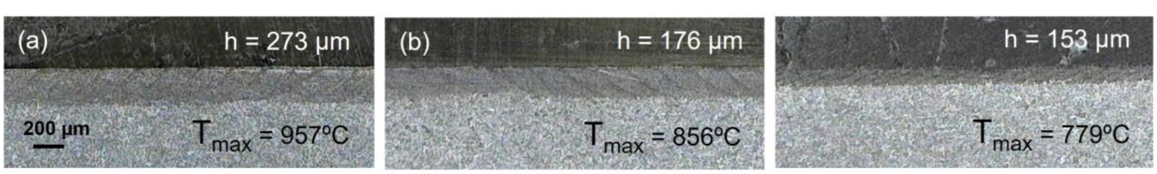

Figure 3: Hardened depth and maximum austenization temperature under different scanning speeds (a) 15 mm/s, (b) 25 mm/s, and (c) 35 mm/s.

Table 3: Design of experiment and experimental results of austenization temperature, and hardened depth.

Experiment no.	**LTH parameters**			**Output responses (Mean)**	
	P (W)	***v* (mm/s)**	**d (μm)**	**T (°C)**	**HD (μm)**
1	90	15	60	924	202.0
2	150	15	60	1182	227.0
3	120	15	60	1081	199.0
4	90	15	100	838	209.0
5	120	15	100	957	273.0
6	150	15	100	1059	309.0
7	90	15	300	848	268.0
8	120	15	300	925	291.0
9	150	15	300	929	289.0
10	90	25	60	726	163.0
11	120	25	60	869	176.0
12	150	25	60	977	225.0
13	90	25	100	761	161.0
14	120	25	100	856	176.0
15	150	25	100	1012	220.0
16	90	25	300	668	0.0
17	120	25	300	710	212.0
18	150	25	300	778	291.0
19	90	35	60	684	0.0
20	120	35	60	803	151.0
21	150	35	60	879	156.0
22	90	35	100	531	0.0
23	120	35	100	779	153.0
24	150	35	100	879	169.0
25	90	35	300	500	0.0
26	120	35	300	500	0.0
27	150	35	300	687	0.0

Table 4: Normalized values, GRC, GRG and rank of responses.

Experiment no.	Normalized		GRC		GRG	Rank
	T	HD	T	HD		
1	0.622	0.654	0.569	0.591	0.580	11
2	1.000	0.735	1.000	0.653	0.827	2
3	0.852	0.644	0.771	0.584	0.678	6
4	0.496	0.676	0.498	0.607	0.552	12
5	0.670	0.883	0.602	0.811	0.707	5
6	0.820	1.000	0.735	1.000	0.867	1
7	0.510	0.867	0.505	0.790	0.648	9
8	0.623	0.942	0.570	0.896	0.733	3
9	0.629	0.935	0.574	0.885	0.730	4
10	0.331	0.528	0.428	0.514	0.471	21
11	0.541	0.570	0.521	0.537	0.529	13
12	0.699	0.728	0.625	0.648	0.636	10
13	0.383	0.521	0.448	0.511	0.479	19
14	0.522	0.570	0.511	0.537	0.524	15
15	0.751	0.712	0.667	0.634	0.651	8
16	0.246	0.000	0.399	0.333	0.366	24
17	0.308	0.686	0.419	0.614	0.517	16
18	0.408	0.942	0.458	0.896	0.677	7
19	0.270	0.000	0.406	0.333	0.370	23
20	0.444	0.489	0.474	0.494	0.484	18
21	0.556	0.505	0.530	0.502	0.516	17
22	0.045	0.000	0.344	0.333	0.339	25
23	0.409	0.495	0.458	0.498	0.478	20
24	0.556	0.547	0.530	0.525	0.527	14
25	0.000	0.000	0.333	0.333	0.333	26
26	0.000	0.000	0.333	0.333	0.333	26
27	0.274	0.000	0.408	0.333	0.371	22

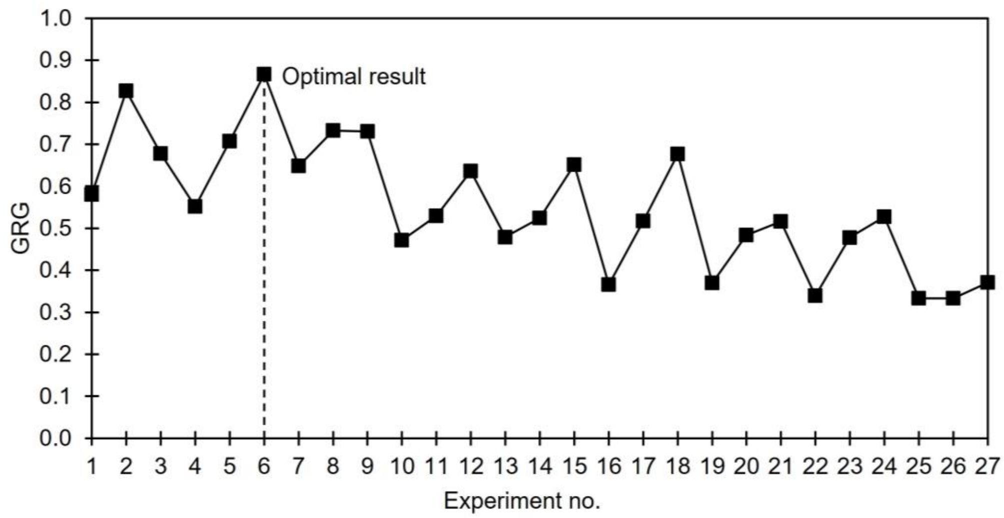

Figure 4: Grey relational grade of individual experimental condition.

Table 5: Response table for LTH parameters.

Level	Laser power	Scanning speed	Track distance
1	0.460	0.702	0.566
2	0.554	0.539	0.569
3	0.645	0.417	0.523
Delta	0.185	0.286	0.046
Rank	2	1	3

Figure 5 shows the main effects of each LTH parameter that visualized the δ and the optimum parameter combination. With respect to Figure 5, the distance between the highest and lowest point of each parameter in the main effects plot represents the δ value. The largest distance between the values is scanning speed, followed by laser power, and track distance providing the least effect on the LTH process. The maximum points of each parameter from the plot represents optimum parameter combination, where the combination of 150 W, 15 mm/s and 100 μm of laser power, scanning speed and track distance, respectively. Thus, confirmed the ranking order from Table 4 as both parameter combinations from the main effects plot and calculation of GRG are the same.

The significance of each parameter, which scanning speed is the highest followed by laser power and track distance. Track distance was the least contributing factor in effecting energy level during track formation, when laser irradiation took place. The energy level required for heating each individual track to the austenization temperature is more affected by the laser power and the irradiation time associated with scanning speed. The lower scanning speed that the optimization process recommended shows that sufficient irradiation time for each track is required for the hardening process to take place. As mentioned by both Babu et al. (2011) and Nath & Sarkar (2018), the sufficient irradiation time and holding time was required during the LTH process to ensure the formation of austenite to take place.

The results obtained when compared to past research were coherent. The decrease in scanning speed while the increase of power resulted in increased hardened depth as mentioned in Dinesh Babu et al. (2013), Martínez et al. (2017), and Muthukumaran & Dinesh Babu (2021), with Martínez et al. (2017) highlighting that scanning speed was significant in affecting the final hardened depth of the workpiece. Compared to the research mentioned above GRA was proven to be viable in optimizing the process parameters for the LTH process.

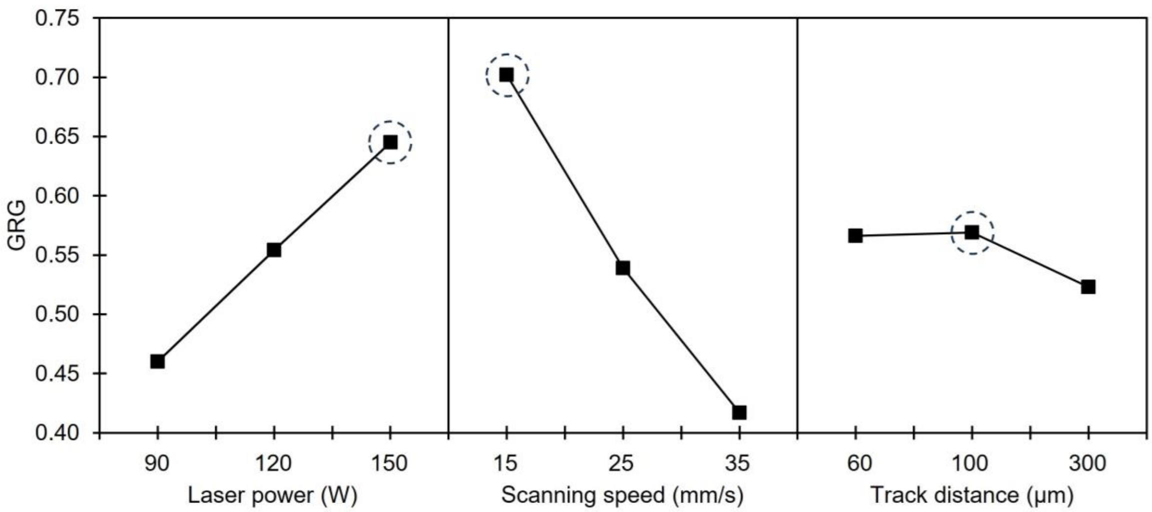

Figure 5: Main effects plot of LTH parameters on the grey relational grade.

CONCLUSIONS

Parametric optimization for laser transformation hardening (LTH) of JIS S50C medium carbon steel was experimentally investigated. Hardening performance characteristics consisted of austenizing temperature, and hardened depth were analysed to attain the optimum hardening parameters using using the grey relational analysis. The optimum parameter combination of laser power 150 W, scanning speed 15mm/s, and track distance of 100 µm was found to have the best effect in maximizing hardening performance. The parameter that is the most significant in effecting the LTH process is scanning speed and followed by laser power. Due to their effect on the irradiation time and total energy irradiated on the specimen surface. Track distance is the least significant parameter in effecting the LTH process. The data obtained through calculation is verified with the response table and main effects plot.

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