Multiple-Objective Optimization Techniques in Laser Joining of Dissimilar Materials Classes: A Comparison between Grey and Ratio Analyses

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***Abstract*—Multiple-objective optimization using grey relational analysis (GRA) has found widespread applications especially in manufacturing and machining processes that involve complex processing parameters and output attributes. On the other hand, multiple-objective optimization on the basis of ratio analysis (MOORA) is often applied in the fields of construction and economy. One distinctive feature of MOORA is the assessment of relative importance of all responses (i.e. weighting ratio) which are taken into account mathematically while GRA emphasis the need of *a priori* information for accurate assignment of weighting ratio. This paper compares these two seemingly different methods by considering their applications in laser joining of dissimilar materials classes in a number of case studies: (a) laser joining of polymer and ceramic, (b) laser joining of polymer and stainless steel, and (c) laser joining of polymer and aluminium alloy. The outcomes of the two methods are compared and discussed. In majority of the cases, the predicted top-ranked alternatives were comparably matched. It is concluded that MOORA is more favourable compared to GRA since it eliminates prior assumption concerning the relative importance of the measured responses, which can lead to unnecessary bias.**

***Index Terms*—Dissimilar Materials; Grey Relational Analysis; Laser Joining; MOORA.**

I. INTRODUCTION

Laser processing for machining process offers versatile functionalities which are otherwise not available in conventional machining methods. The non-contact and localized nature of the laser processing has led to product miniaturization especially in the field of smart medical [1], micro-electro-mechanical (MEMS) and bio-MEMS devices [2]. Often these devices are assembled using a variety of dissimilar materials such as ceramics, polymers, metals and glass. Selection of these types of materials depends on the application and working of devices. More often these dissimilar materials are joined together to derive advantage or complement benefits. However such joining process is complex and challenging due to dissimilar nature and properties of combining substrates. The combination process is influences by the physical, chemical, thermal and optical properties of the substrate materials. In these scenarios, laser joining has enjoyed some success compared to other conventional techniques [3].

Amongst other material classes, combination of polymers with ceramics has numerous applications in microfluidics, biosensors and lab-on-a-chip systems especially for analytical instrumentation. One example is replacement of brittle and relatively heavy glass substrate, often used as optical window, with transparent, biocompatible and lightweight polyimide polymer. While ceramic substrates can be used as an enclosure or housing due to their chemical resistant nature in adverse environments. However, a few studies can be found in the literature regarding joining these two materials. One of the key studies is of Kawahito et al. [4], which performed the joining process between Si_3N_4 ceramic and polyethylene terephthalate (PET) polymer using a diode laser (λ = 940 nm), and obtained an optimum bond strength of 3100 N at laser power of 170 W and scanning speed of 4 mm/s. Recently, Tamrin et al. [5] highlighted some important joint characteristics that may contribute to the overall strength of the joint. They studied the characteristics of lap joint between polymer and ceramic using CO_2 laser. Moreover, an optimal configuration of laser source parameters was also estimated using Grey relational analysis (GRA).

Joining of metals with polymers has also gained some interests due to its wide range of applications. For instance, titanium is an excellent biocompatible material having applications for implantable microsystems [6] and medical implants [7] when combined with polyimide. In a study related to laser joining, titanium was joined with KaptonFN composite for the application in electronics packaging [8]. Results on the joining process of PET and 316L stainless steel is reported by Wang et al. [9] using response surface methodology. While Yusof et al. [10] investigated the effects of anodization and laser process parameters on the resultant joint strength (nominal joint strength, shear strength and molten pool depth) between PET and A5052 aluminium alloy. Yusof et al. observed that the resultant joint strength increases with the increase of heat input and pulse duration, however the relationship is non-linear; the details are included in forth coming sections.

Understanding the relationship between the process parameters and resultant joint characteristics of dissimilar materials is important. Usually controlled sets of experiments are used to deduce such relationships and design of experiment techniques prove quite useful. For instance, design of experiment using Taguchi method provides methodical approach where effect of a singular process parameter on a singular joint characteristic can be studied independently. While, response surface methodology provides the overall response of more than one process parameter on a single joint characteristic. However, both approaches have some drawbacks in the real manufacturing environment as there are numerous process parameters and materials characteristics that need to be judiciously selected based on more than several joint characteristics. Because Taguchi and response surface methodology are inherently time-consuming in such situations since the effective relationships take more precedence, they appear no longer applicable.

Most experimental studies are unstructured with incomplete datasets. Moreover, realization of influential process parameters and their relationships with different joint characteristics are elusive in nature. For such multi-objective scenarios, findings best possible set of process parameters for desired or most probably results becomes a task. Such multi-objective optimization can be achieved using variety of multi-objective decision-making (MODM) methods. One such method uses the idea of basis of ratio analysis (MOORA) method to optimize processes, while Grey relational analysis (GRA) is slightly more involved method that is commonly used in the studies of laser joining of dissimilar materials classes [3]. One important distinguishing feature between the two optimization techniques is that GRA emphasizes the requirement of knowing the relative importance of all responses (i.e. weighting ratio). This information is usually derived through extensive experimental investigation and material characterization [11-14]. While at times this is done through random assumptions which can lead to bias in estimations. On the other hand, MOORA relaxes such a requirement through ratio analysis [15, 16].

In this paper, we present applications of MOORA and GRA methods in various laser joining of dissimilar materials classes and their results are discussed.

II. EXPERIMENTAL SETUP

In a laser lap joining, two different materials of reasonable thicknesses are initially clamped before being illuminated using a concentrated laser beam. Often, the transparent material at the top transmits laser heat to the lower absorbent surface to allow melting at the interface. The desired joint is created at the interface upon re-solidification. The arrangement is however, depends on material's absorptivity with respect to the applied laser's wavelength. For instance, Nd:YAG laser can penetrate through most of the transparent polymers whereas CO_2 laser results in thermal degradation to the same polymer. Detailed description of laser lap joining process and parameters affecting the process and joint strength are discussed by Tamrin et al. [3].

III. MULTIPLE-OBJECTIVE OPTIMIZATION RATIO ANALYSIS (MOORA)

Multiple objective optimization ratio analysis carries out simultaneous optimization of multi-attributes in a set of constraints. This methodology, proposed by Brauers et al. [17], has been used for numerous problems in the fields of construction [18] and economy [17, 19], and recently being employed in manufacturing problems [20]. MOORA is a matrix based method which starts with a decision matrix (as shown in Eq. 1). A typical decision matrix usually comprises of performances of different alternatives with respect to various objectives.

$$X = \begin{bmatrix} x_{11} & x_{12} & \dots & \dots & \dots & \dots & x_{1n} \\ x_{21} & x_{22} & \dots & \dots & \dots & \dots & x_{2n} \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ x_{m1} & x_{m2} & \dots & \dots & \dots & \dots & x_{mn} \end{bmatrix} \quad (1)$$

where x_{mn} represents the performance measure of m^{th} variable on n^{th} attribute/objective. The second step involves the calculation of all the performances of i^{th} alternative for j^{th} attribute with respect to representatives of all the alternatives concerning the attribute. The ratio is calculated as the square root of the sum of squares of each alternative per attribute expressed as:

$$\overset{a}{x}_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \quad (j = 1, 2, \dots, n) \quad (2)$$

where $\overset{a}{x}_{ij}\ \overset{a}{x}_{ij}\ \overset{a}{x}_{ij}\ \overset{a}{x_{ij}}$ is the normalized performance which ranges from [0, 1]. For calculation of multi-objective optimization configuration, these normalized parameters are summed or subtracted depending on the maximization of beneficial attributes or minimization of non-beneficial attributes as:

$$\bar{y}_i = \sum_{j=1}^{g} w_j \cdot \overset{a}{x}_{ij} - \sum_{j=g+1}^{n} w_j \cdot \overset{a}{x}_{ij} \quad (j = 1, 2, \dots, n) \quad (3)$$

With the total number of maximized attributes are represented by g while $(n-g)$ represents the number of attributes for minimization. The normalized assessment value is represented by $\bar{y}_i$ for i^{th} alternative compared to all attributes. For the case when a specific attribute is of higher importance than others, a weighing parameter w_j (for j^{th} attribute) can be included. Ordinal ranking of the value of $\bar{y}_i$ indicates the final preference while the sign indicates the maxima or minima of attribute; positive for maxima-beneficial attributes and negative value for minima-negative attribute.

IV. GREY RELATIONAL ANALYSIS

Grey relation analysis (GRA) estimates the best suitable configuration in a given set of variables. The procedure starts with the normalization of attributes of the multi-objective function. The desired characteristics of categorize as 'higher-the-better' or 'lower-the-better' and the normalized attribute, x_{ij}, can be expressed as:

$$x_{ij} = \frac{y_{ij} - \min_j y_{ij}}{\max_j y_{ij} - \min_j y_{ij}} \quad (4)$$

$$x_{ij} = \frac{\max_j y_{ij} - y_{ij}}{\max_j y_{ij} - \min_j y_{ij}} \quad (5)$$

The index i of the normalized attribute is the quality characteristic of the j^{th} experiment. The second step involves a comparison of actual experimental data with an ideal set of data using relational coefficients, ξ_{ij}.

$$\xi_{ij} = \frac{\min_i \min_j \left| x_i^0 - x_{ij} \right| + \zeta \max_i \max_j \left| x_i^0 - x_{ij} \right|}{\left| x_i^0 - x_{ij} \right| + \zeta \max_i \max_j \left| x_i^0 - x_{ij} \right|} \tag{6}$$

Here x_i^o represents the normalized value for the ideal experiments with maximum value of 1.0 for the ith quality characteristics. While the distinguishing coefficient ξ ranges between [0,1], however value of 0.5 is usually used in most cases. The next step is the calculation of Grey relational grade, which is a direct indicator of the multiple quality characteristics. It is calculated after summation of relevant grey relational coefficients for each experimental set multiplied with a weighing function.

$$\gamma_j = \frac{1}{m} \sum_{i=1}^{m} w_i \xi_{ij} \tag{7}$$

γ_j is the Grey relational grade for the j^{th} experiment with w_i represents the weighting factor for the ith quality characteristic. The summation is carried over m number of quality characteristics.

V. DECISION MAKING PROBLEMS

Here a comparison has been made between the predictions of optimal configuration using the two optimization techniques for the laser joining process. Four experimental studies related to laser joining of different material classes are selected for the analysis. The selected material classes are detailed below:

1. Laser joining of polyethylene terephthalate glycol (PETG) with glass-ceramic (Tamrin et al. [5])
2. Laser joining of PET and 316L stainless steel (Wang et al. [9])
3. Laser joining of PET and A5052 aluminium alloy (Yusof et al. [10])

Details of each study can be found in the relevant reference. Some relevant details and results are presented here followed with analysis using both MOORA and GRA. The comparisons of optimal configurations predicted by two techniques are presented for each case study followed by related discussions.

A. Laser joining of PETG and glass ceramic

This study is related to laser joining of PETG (polymer) with glass-ceramic. In a recent analysis, Tamrin et al. [5] determined the optimal configuration set of process parameters by employing full-factorial experimental design in combination with GRA. The multi-objective performance measure included joint width, kerf width and tensile strength of the joint. Here, for the sake of completeness, summary of the experiments and results are tabulated in Table 1. While the corresponding grades for the experiments as determined by GRA and MOORA are presented in Table 2.

Table 1
Experimental layout and multi-performance results for laser joining of PETG and glass-ceramic (after Tamrin et al. [5])

Exp. no.	Joining parameters			Mean joint width (µm)	Mean kerf width (µm)	Joint tensile strength (N)
	Power (W)	Stand-off distance (mm)	Speed (mm/s)			
1	40	16	10	1671	1285	247.28
2	40	16	15	1767	1080	251.38
3	40	16	20	1028	1145	156.7
4	40	23	10	2731	1482	314.94
5	40	23	15	2145	1374	245.26
6	40	23	20	1510	1273	221.15
7	40	30	10	2912	1663	261.93
8	40	30	15	2084	1522	242.47
9	40	30	20	1819	1474	253.31
10	40	37	10	2823	2056	321.63
11	40	37	15	2008	1687	235.16
12	40	37	20	1542	1321	226.44
13	40	44	10	2992	1470	294.94
14	40	44	15	1980	980	202.04
15	40	44	20	1598	1313	134.47
$\sum_{j=1}^{15} x_{ij}^2$				67251293.58	30752216.25	904619.27
$\sqrt{\sum_{j=1}^{15} x_{ij}^2}$				8200.69	5545.47	951.11

Table 2
Normalized decision-making matrix and results of multi-objective analysis for laser joining of PETG and glass-ceramic

Experiment no.	Joint width	Kerf width	Tensile strength	$\bar{y}$	MOORA rank	GRA rank
1	0.2037	0.2317	0.2600	0.6955	9	5
2	0.2155	0.1948	0.2643	0.6746	10	4
3	0.1254	0.2064	0.1648	0.4966	15	6
4	0.3330	0.2672	0.3311	0.9314	3	2
5	0.2615	0.2477	0.2579	0.7671	7	11
6	0.1841	0.2296	0.2325	0.6462	12	9
7	0.3551	0.2998	0.2754	0.9303	4	12
8	0.2542	0.2745	0.2549	0.7836	6	13
9	0.2218	0.2658	0.2663	0.7540	8	8
10	0.3443	0.3708	0.3382	1.0532	1	1
11	0.2449	0.3042	0.2472	0.7963	5	14
12	0.1881	0.2383	0.2381	0.6644	11	10
13	0.3648	0.2651	0.3101	0.9400	2	3

The comparison shows that the outcome of MOORA matches well with the outcome of GRA for first three ranks. This confirms that the relative important or weights assigned for GRA are reasonable. Experimental set 10 is predicted by both analyses to be rank first. The first three positions, predicted by both analyses, have one common feature which is the joining speed. The lower speed of joining along with moderate/intermediate stand-off distance provides the desired results. While experiment number 15 has lowest GRA and second worst rank by MOORA. Experiment 15 is amongst the undesired scheme of process parameters amongst the dataset with high joining speed and stand-off distance. While disparity can be observed between MOORA and GRA outcomes when small stand-off distance is used irrespective of joining speeds. As observed in experiment number 1, 2 & 3, MOORA predicts lower ranks compared to intermediate ranks assigned by GRA. This is due to weight functions which are assigned before analysis for GRA analysis, while MOORA adjusts the relative importance of response itself so that no bias appears in the outcome. A closer examination of data sets reveal that experiment number 3 has low tensile strength of joint, only better than experiment no. 15 which has lowest amongst the dataset. On the other hand, GRA ranks experiment no. 3 at 6th place. Moreover, GRA analysis does not provide clear picture on the influence of stand-off distance, however MOORA clearly indicates the influence in its prediction. Also the difference in the process parameter of stand-off distance seems to influence the kerf width more appreciably than other measured parameters as noted in Table 2.

While comparing MOORA with GRA predictions, it is imperative to mention such inconsistencies have been reported earlier as well. Gadakh et al. [15] reported some inconsistencies when comparing results of GRA and MOORA for submerged arc welding process. The discrepancy was mainly attributed to the inherent mathematical methods used to linearize each response according to the desired characteristic. For instance, tensile strength is preferable to be high while kerf and weld widths are desired to be small. Rank one awarded by GRA corresponds to maximum tensile strength achieved by the weld, moreover a slight difference in the tensile strengths between rank 2 and rank 1 GRA results is seen. This indicates that in the considered case study, the rank 1 option is the most suitable configuration as favored by both analyses. However GRA is quite sensitive and slight variations in the process parameters and observed/measured response seem to influence the outcome significantly.

B. Laser joining of PET and 316L stainless steel

The second case study considered here is the experimental data of Wang et al. [9] where relationships between laser process parameters and the corresponding responses in laser joining of PET and stainless steel could not be deduced directly. It was observed that both joint strength as well as joint seam increase with the rise of laser power, while both decrease with the increase of joining speed. However, the joint strength appears non-linear related to process parameters and the joint seam increases linearly with the increase of stand-off distance.

For sake of discussion, summarized data set of the case study is presented in Table 3. It is important to mention here that equal joint widths are noted for experiment number 9 and 3 despite having different joining parameters, however that the joint strength in the former experiment is about 8.8% greater than that of the latter. While experiment number 7 and 3 have equal joint strengths with different joint widths at similar laser power and joining speed. The key difference between experiment number 7 and 3 is the stand-off distance, which is around four times larger for experiment number 7 compared to experiment number 3.

Table 3
Experimental layout and multi-performance results for laser joining of PET and 316L stainless steel (after Wang et al. [9])

Experiment no.	Joining parameters			Joint width (mm)	Joint strength (MPa)
	Power (W)	Stand-off distance (mm)	Speed (mm/s)		
1	13.62	0.81	96.49	2.15	73.03
2	18.38	0.81	96.49	3.17	97.77
3	13.62	0.81	203.51	1.34	61.56
4	18.38	0.81	203.51	1.94	85.69
5	13.62	3.19	96.49	2.45	76.65
6	18.38	3.19	96.49	3.44	99.58
7	13.62	3.19	203.51	1.84	61.56
8	18.38	3.19	203.51	2.6	78.46
9	12	2	150	1.34	66.99
10	20	2	150	2.99	91.44
11	16	2	60	2.99	89.35
12	16	2	240	1.85	67.59
13	16	0	150	2.04	57.94
14	16	4	150	2.68	68.57
15	16	2	150	2.52	87.21

Moreover, it is important to highlight the influence of joint width on joint strength. As shown in Figure 1, overall trend is a linear relationship between the two; however, an increase in joint width does not necessarily guarantee an increase of joint strength, as observed in experimental data. In application of implantable microsystem, good joint strength with minimum joint width is desired. Therefore, owing to the important, it is concluded that the joint strength is assigned twice as much weight compared to weld width for GRA procedure, such that:

$$\text{joint strength} : \text{joint width} = 1 : 2 \qquad (8)$$

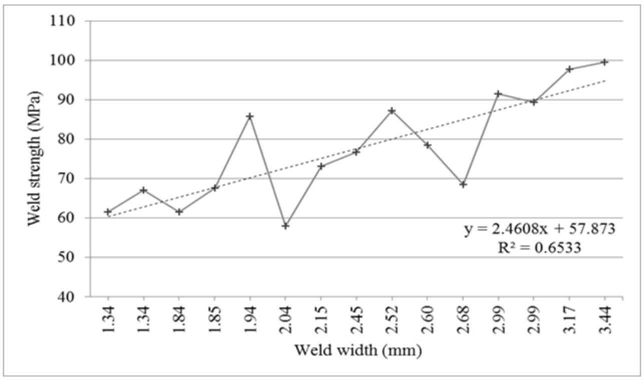

Figure 1: Joint strength versus joint width for laser joining of PET and 316L stainless steel.

Here both GRA and MOORA procedures are employed to conduct multi-objective optimization. The normalized values for each response concerning laser joining are tabulated in Table 4. Both analyses show that experiment number 6 produces the optimum response at laser power of 18.38 W, stand-off distance of 3.19 mm and joining speed of 96.49 mm/s. This is followed by experiment number 2 at same laser power and joining speed of experiment no. 6 albeit the stand-off distance which is remarkably lowered to just 0.81 mm. Rank 1 and 2 experimental setups indicate that stand-by distance has lower influence on the outcomes of the joining process especially the tensile strength of joint.

Apart from rank 1 and 2, the predictions of GRA and MOORA deviate significantly for lower ranks. For instance, the lowest rank predicted by GRA corresponds to experiment no. 14 which is assigned rank 8th by MOORA. Interestingly rank 15th experiment estimated by MOORA is ranked 8th by GRA. Apparently there is not much similarity between the two experiments i.e., experiment number 3 and 14. In order to understand this ambiguity, one may have a close look at the data and Figure 1. As noted, higher joint widths are likely to yield higher tensile strengths of the joint. Experiment number 14 has reasonably higher joint width (2.68 mm), yet it has yield strength on the lower side (68.57 MPa). This response has led MOORA to assign worst ranking amongst the complete data set. Similarly experiment no. 13 also does not enjoy good rankings. While experiment number 3 has lower joint width therefore the corresponding joint strength is low as well. This is expected as seen by the trend presented in Figure 1. However, GRA assigns worth rank to experiment 3, corresponding to lower width as well as low joint strength. It can be seen here that MOORA tends to predict the correlation behaviour and select the outliers at the extreme ranking points. While GRA compares the desired outcomes with measured responses and rank the data set on absolute terms.

C. Text Laser joining of PET and A5052 aluminium alloy

In all two previous case studies and other relevant literature, the applications of MOORA as well as GRA have been mainly limited to singular materials having multiple characteristics. Here a case study is selected to apply these techniques on materials whose surfaces undergo modifications such as anodization, sputter coating and/or plasma coating etc. Yusof et al. [10] studied joint characteristics of treated (anodized) and non-treated (as received) samples with PET. By varying heat input and pulse duration, the nominal joint area, shear strength and molten pool depth were measured and are reproduced in Table 5.

Table 4
Normalized decision-making matrix and results of multi-objective analysis for laser joining of PET and 316L stainless steel.

Experiment no.	Joint width	Tensile strength	$\bar{y}$	MOORA rank	GRA rank
1	0.2280	0.2397	0.6916	10	6
2	0.3362	0.3209	0.6571	2	2
3	0.1421	0.2020	0.6172	15	8
4	0.2057	0.2812	0.6103	9	3
5	0.2598	0.2516	0.5535	7	12
6	0.3648	0.3268	0.5332	1	1
7	0.1951	0.2020	0.5114	13	13
8	0.2757	0.2575	0.5093	6	10
9	0.1421	0.2199	0.487	14	5
10	0.3171	0.3001	0.4677	3	4
11	0.3171	0.2933	0.418	4	6
12	0.1962	0.2218	0.4065	11	9
13	0.2163	0.1902	0.3972	12	14
14	0.2842	0.2251	0.362	8	15
15	0.2672	0.2862	0.3441	5	7

Table 5
Experimental layout and multi-performance results for laser joining of PET and A5052 aluminium alloy (after Yusof al. [10])

Exp. No.	Joining parameters		Nominal joint area (mm²)		Shear strength (MPa)		Molten pool depth (mm)	
	Heat input (J)	Pulse duration (ms)	As received	Anodized	As received	Anodized	As received	Anodized
1	5.9	5	1.250	2.150	2.46	4.11	0.029	0.029
2	18.6	10	2.675	3.225	2.86	4.18	0.039	0.043
3	34.9	15	3.025	3.875	3.04	6.18	0.053	0.083
4	55.8	20	4.775	5.400	6.46	8.46	0.089	0.158
$\sum_{j=1}^{15} x_{ij}^2$			40.669	59.199	65.24	144.15	0.013	0.035
$\sqrt{\sum_{j=1}^{15} x_{ij}^2}$			6.377	7.694	8.08	12.01	0.114	0.186

Table 6
Normalized decision-making matrix and results of multi-objective analysis for laser joining of PET and A5052 aluminium alloy

Exp. No.	Nominal joint area		Shear strength		Molten pool depth		$\bar{y}$		MOORA Rank		GRA Rank	
	As received	Anodized	As received	Anodized	As received	Anodized	As received	Anodized	As received	Anodized	As received	Anodized
1	0.1960	0.2794	0.3051	0.3421	0.2515	0.1544	0.3606	0.2170	3	3	4	4
2	0.4195	0.4192	0.3537	0.3480	0.3444	0.2297	0.2787	0.1586	4	4	3	3
3	0.4743	0.5036	0.3758	0.5146	0.4619	0.4481	0.3634	0.4591	2	2	2	2
4	0.7487	0.7018	0.8003	0.7050	0.7774	0.8499	0.8290	0.8531	1	1	1	1

The results of MOORA and GRA are shown in Table 6. In general, both analyses show similar trends in their rankings. Their results indicate that nominal joint area, shear strength and molten pool depth increase with the increase in heat input and pulse duration. Although the number of experiments is not appropriate, however the results indicate that maximum shear strength with minimum nominal joint area and deeper molten pool is achieved in experiment number 4, which is ranked first by both MOORA as well as GRA. While the effect of anodizing seems to have no apparent effect on the overall ranking, however in absolute sense, anodizing increases the shear strength of the joint. However, it results in increase of joint area as well.

In general, the joint characteristics are significantly better for as received sample at regimes of low heat input and short pulse duration as anodized layer requires extra heat input and time to melt. The trend reverses towards high heat input and long pulse duration, see experiment number 3 and experiment number 4. At maximum heat input and pulse, anodized sample is marginally better than that of as-received sample.

VI. CONCLUSIONS

In this study, multiple-objective optimization on the basis of ratio and grey relational analyses were investigated to determine the optimized laser lap joining process parameters having multiple quality characteristics. The multiple quality characteristics of laser lap joining process using these two methods were simplified to single performance characteristics known as normalized assessment value and grey relational grade, respectively. Three actual examples were considered to demonstrate and compare these two methods systematically. In majority of the cases, the predicted top-ranked alternatives were comparably matched. Both MOORA and GRA are computationally very straightforward and robust. However, MOORA is more favourable as it eliminates prior assumption concerning the relative importance of the measured responses.

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