Optimization of Laser Transmission Welding Process Parameters Using Single Objective and Multi Objective Optimization Technique

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Abstract - *In this research work, the study was made to optimize laser transmission welding process parameters namely laser power, scanning speed and number of passes by using single objective and multi-objective optimization technique and to investigate the influence of process parameters on the laser-welded joints of polypropylene and polypropylene composite. Statistical software Minitab was used to establish the design matrix and to obtain the regression equations. L9 Orthogonal array was considered with three factors at three different levels, as a response lap shear pull test and weld width measurement were performed. Taguchi method was used as single objective optimization technique to optimize process parameters considering individual quality characteristics. To determine the parameter having a greater influence on the responses and to check the adequacy ANOVA was used. Grey relation analysis was performed to find out the combined optimal combination of process parameters for both maximum weld strength and minimum weld seam width. SEM was performed for the examination of the cross-sections and the surface of weld seams.*

***Key Words*: Laser transmission welding, Polypropylene, Polymer, Grey relational analysis, Jute fiber reinforced polypropylene.**

1. INTRODUCTION

Plastics and their composites are being used widely all over the world in many of the industries for manufacturing of toys, utensils, automotive parts, aerospace parts and also in medical use, because to their properties such as low weight, low cost, decent strength to weight ratio, better corrosion resistance and ability to take good finish. Composite materials are the combination of more than one material with different properties. There are numerous advantages of using natural fibers for reinforcement in polymers. The most important benefits are low cost, biodegradability and renewability [1-3].

A part from mechanical fastening and adhesive bonding, many other joining techniques can be used such as a. Thermal welding b. Friction welding and c. Electromagnetic welding. Further the thermal plastic welding is classified as a. Hot air welding b. Hot tool welding c. Laser beam heating and d. Infrared heating [4]. In late 60's laser welding of plastics was introduced and became popular in last decades because of great significant reduction in cost of laser energy used. Basically two types of laser welding are proposed and those are surface heating and laser transmission welding (LTW). In surface heating process only surface is heated and fused with other parts. Laser transmission welding is a very popular mode of the operation as it offers many benefits when it is compared with surface heating which includes speed, flexibility and weld quality [5-6]. The main principle of laser transmission welding is, one part should be transmittive and another absorptive to laser energy. If both are transparent part, then to make transparent part absorptive to laser energy, the pigment Titanium dioxide TiO_2 can be used [7]. For laser transmission welding the material shouldn't be highly reflective and must be free of energy transitions in this wavelength region [8].

Moskvitin G V et al.[9] studied laser welding of plastics process and different methods and types of laser used for laser transmission welding were discussed. In this study three important conditions for laser transmission welding were discussed, such as high temperature should reach the level of material, tight contact of welded surface and optimum holding time because the plastic material requires certain period of time for cooling. Chiara mandolfino et al. [10] performed laser welding of polypropylene with no additives with two different sources of lasers, fiber laser and CO_2 laser. Three parameters such as irradiance, residence time and clamping pressure were considered to design L9 array. Tensile test was performed to analyze weld joint. It was found that fiber laser is more significant than CO_2 laser. To improve the weld strength and weld quality of laser welded specimen the process parameters has to be optimized. Quality of weld depends on many different parameters such as scanning speed, laser power, laser beam diameter, irradiation time, standoff distance and clamp pressure etc. Combination of laser welding process parameters is the key point to obtain high weld strength and welding quality. The most powerful problem solving tool is Taguchi method, which can improve the process, design, and performance of product quality with decrease in cost and time of experiment. ANOVA is the best tool to investigate which process parameters significantly affect the quality characteristics [11]. The joints produced within the optimal process parameter range were free of any internal or external defects [12].

Abed S et al. [13] investigated welded zones of polypropylene material with different carbon black content in lap joint configuration using diode laser of 20W. It was observed that the process parameters and optical properties of absorbing polymer both have a greater influence on weld seam. Crystanillity index of the material reaches maximum by decreasing laser power and increasing its speed [14]. Mingliang chen et al. [15] studied effects of carbon black on the laser welding of plastics. Bouguer-lambert law and an apparent absorption co-efficient were used to describe the total energy attenuation in scattering polymers with and without carbon black. Unreinforced polymers such as polypropylene (PP), nylon 6 (PA6) and glass fiber reinforced polymers namely polypropylene, nylon6 (PA6GF) and polycarbonate were used. It was found that the laser energy is attenuated more rapidly in PA6GF than that of PA6 for same weight percent loading. This was because of increased light scattering by glass fiber and higher density reinforced materials. The moisture content of the material affects the quality of weld seam [16]. Wipppo V et al. [17] conducted an experiment to investigate the temperature distribution over the weld seam, for the laminates of carbon fiber reinforced polyphenylene sulfide (CFRP UD) specimens of thickness 1.2mm. The laser welding was performed by using diode laser of 300W. Infrared camera was used to monitor process temperature and it was found that inhomogeneous temperature distribution could lead to non-uniform weld seam & also decrease in strength of weld seam. Bappa Acherjee [18] performed an experiment to weld polycarbonate using laser transmission welding and investigated the effects of processing parameters to obtaining high quality weld joints. Deign of experiments were performed with four factors each at five levels to obtain different combination of laser welding process parameters. Laser power, welding speed, standoff distance and clamp pressure were considered as four factors and 30 sets of experiments were performed. It was found that, higher values of laser power, standoff distance and lower values of welding speed leads to higher weld strength. Wenjie Ren et al. [19] performed a comparative study on fiber laser and CO2 laser welding on Inconel 617 specimen of size (35mmx15mmx5mm) with butt joint configuration. It was shown that high power CO2 laser was suitable for post welding of joints which can be able to create a high ratio of depth to width in bed and it was found that melting efficiency of fiber laser was higher than CO2 laser. Tamrin K F et al. [20] investigated CO2 laser process parameters on the characteristics of spot welded joint between ceramic and thermoplastic. Eight numbers of experiments were performed to weld, as a response tensile strength was formed. The effect of standoff distance was found quite insignificant in the mean weld diameter and by increasing laser exposure and number of spots, the weld strength can be improved. Increasing laser exposure duration will increase mean weld diameter, while number of spots seams to affects the mean weld diameter at lower exposure duration mainly. At lower laser power it was observed that it lead to inconsistent power prevalence which causes a strong variation of mean spot diameter at lower exposure durations.

Quadrini F et al. [21] performed welding of polyethylene (High density polyethylene) with two different techniques. Hot tool welding and laser welding were used to weld the HDPE specimens of 3mm thickness and comparison between both the processes was performed. The laser welded joints got lower strength compared to hot tool welding, but the laser welding process can be used where hot tool plate welding can't be applied. It was found that the unfilled polymers requires high amount of laser power to achieve surface temperature and it was suggested that the use of inert gas is very important to achieve aesthetic weld joint by avoiding degradation of materials and burning. Kritsky A et al. [22] performed laser transmission welding to weld tube with a plate of nylon material. Conical mirrors have been used to guide laser beam along the welding plate at the outer circumference of tube. This study gave a proof that, the laser transmission welding can be used for any kind of geometry. Anahi Pereira da Costa et al. [23] studied welding technologies for thermoplastic composites in aerospace applications. Improved properties and low cost processes in thermoplastic composites technology are the main reasons due to which it is widely used in aerospace applications. It is concluded that not all plastics can be welded by same welding techniques, different techniques for different materials and situations are needed. Application of laser transmission welding depends on its specific requirements. There bonding processes are very beneficial which includes reduced surface preparation requirements, reprocessing, recyclability and improved durability.

It has been found that while a lot of research work has been done on the laser transmission welding, Influence of process parameters such as laser power, scanning speed and standoff distance on the laser welded joint has been studied, but influence of number of passes on the laser welded joint is rarely studied. Many plastic materials are being welded using laser welding process, but there is less work done on laser welding of polypropylene and jute fiber reinforced polypropylene. Hence the present study is carried out to optimize the laser transmission welding process parameters by using single objective and multi objective optimization techniques and to investigate influence of laser transmission welding process parameters such as laser power, scanning speed and number of passes on the laser welded joints of polypropylene with polypropylene and polypropylene with jute fiber reinforced polypropylene.

2. EXPERIMENTAL WORK

2.1 Materials and experimental set-up

In this research work, natural, black (containing 0.5wt% carbon black as colour pigment) and jute fiber reinforced polypropylene plaques of dimensions 80mm x 35mm x 4mm each, cut from compression moulded sheets are used as shown in Fig. 1.

Fig -1: (a) Natural polypropylene, (b) Black polypropylene, (c) Jute fiber reinforced polypropylene

Germany IPG system machine equipped with 30W fiber laser with a beam diameter of 1300μm was used as a tool for welding natural polypropylene with black polypropylene and natural polypropylene with jute fiber reinforced polypropylene. The specimens were placed on the work table and were clamped in a lap joint configuration, using a constant holding pressure of 30N and with a constant standoff distance 187 mm. Transparent part was placed on top and opaque part was placed at bottom. The weld seam was targeted at the length of about 10mm from the end of natural polypropylene. The cover length in the specimens was considered as 20 mm as shown in Fig. 2. Every lap joint for experiment was comprised of one natural polypropylene (transparent) and another black polypropylene (opaque). Similarly for another set of experiments natural polypropylene (transparent) and jute fiber reinforced polypropylene (opaque) with lap joint configuration.

2.2 Design of Experiment

To study the influence of process parameters, a L9 orthogonal array was designed by using Minitab software considering three factors each at three different levels. The three controllable process parameters considered to carry out the experiments were laser power (P), Scanning speed (SS) and Number of passes (N). The factors and levels considered for the welding of natural polypropylene with black polypropylene specimens are given in Table 1 and the factors and levels considered for the welding of natural polypropylene with jute fiber reinforced polypropylene specimens are given in Table 2.

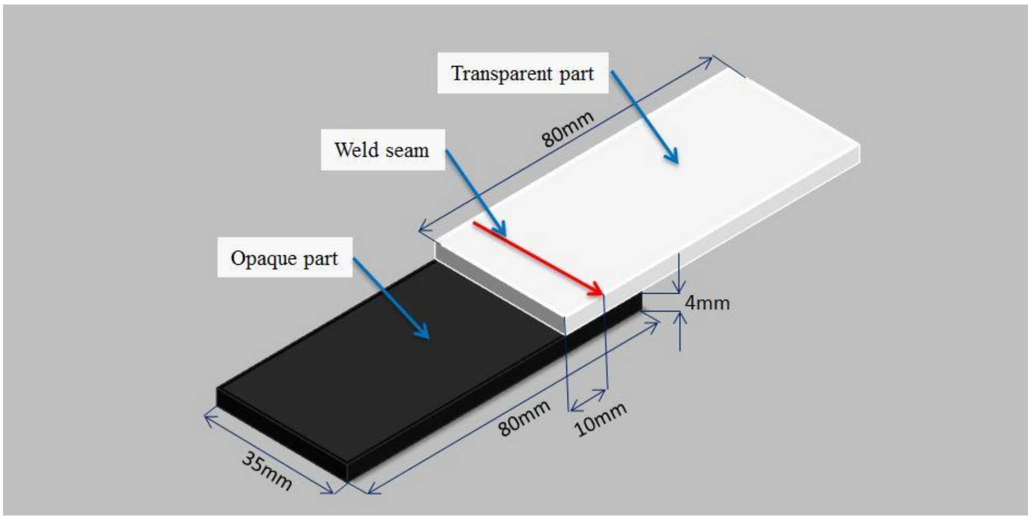

Fig -2: Lap joint configuration

Table -1: Laser welding process parameters and their levels to weld natural polypropylene with black polypropylene

Factors	Unit	Levels		
		Level 1	Level 2	Level 3
Laser Power-P	Watt	25.5	27	28.5
Scanning speed-SS	mm/min	300	400	500
Number of passes-N		15	20	25

Table -2: Laser welding process parameters and their levels to weld natural polypropylene with jute fiber reinforced polypropylene

Factors	Unit	Levels		
		Level 1	Level 2	Level 3
Laser Power-P	Watt	25.5	27	28.5
Scanning speed-SS	mm/min	300	400	500
Number of passes-N		70	75	80

2.3 Evaluation of Weld Qualities

The lap shear pull test was proposed as tensile test of two welded overlapped pieces of materials. A Tensometer Model PC-2000, microprocessor controlled mini tensile testing machine was used for lap shear pull test, for evaluation of their relative strengths. The lap shear joints of both natural polypropylene with black polypropylene welded specimens and natural polypropylene with jute fiber reinforced polypropylene welded specimens were tested at 23°C with a 50mm gauge length at a cross head speed of 10mm/min and shear strength was calculated as the maximum load to failure per unit length of the weld. After failure of specimens, all the specimens were observed in EV Series Vision Management Machine to measure weld seam width with an accuracy of 0.005mm. For each specimen along the weld seam at three different locations 1, 2, 3 the weld width was measured as (W1, W2, W3) and mean (W) was considered as a weld seam width of that specimen. The weld strength and weld seam width results for natural polypropylene with black polypropylene welded specimens are presented in Table 3 and results for natural polypropylene with jute fiber reinforced polypropylene welded specimens are presented in Table 4.

3. RESULTS AND DISCUSSION

3.1 Taguchi method and Analysis of Variance

Taguchi method uses the concept of signal to noise ratio. The signal represents the input parameters that can be controlled and noise represents the input parameters that cannot be controlled. To find effect of each factor on the output (Responses) the signal to noise ratio need to be considered for each experiment. There are three variants to calculate SN ratios and those are smaller the better (Equation 1), Larger the better (Equation 2) and nominal the best (Equation 3). Depending on the characteristics and responses these cases are considered [11]. To calculate SN Ratios for weld strength "larger the better" variant is used and to calculate SN ratios for weld seam width "smaller the better" is used. The results for SN ratios are as present in Table 3 for natural polypropylene with black polypropylene welded specimens and SN ratios for natural polypropylene with jute fiber reinforced polypropylene welded specimens are presented in Table 4.

Table -3: Design matrix and experimentally measured responses for natural polypropylene with black polypropylene welded specimens

Exp. No	Laser power (W)	Scanning speed (mm/min)	Number of passes	Tensile shear strength (N/mm²)	Weld width (mm)	SN ratio Strength	SN Ratio Width
1	25.5	300	15	14.194	5.289	23.042	-14.467
2	25.5	400	20	10.196	4.167	20.169	-12.396
3	25.5	500	25	11.789	4.897	21.430	-13.799
4	27	300	20	16.418	6.09	24.306	-15.692
5	27	400	25	15.806	6.27	23.976	-15.945
6	27	500	15	2.884	2.607	9.200	-8.323
7	28.5	300	25	15.391	6.279	23.745	-15.958
8	28.5	400	15	7.721	4.957	17.753	-13.904
9	28.5	500	20	10.386	5.277	20.329	-14.448

Table -4: Design matrix and experimentally measured responses for natural polypropylene with jute fiber reinforced polypropylene welded specimens

Exp. No	Laser power (W)	Scanning speed (mm/min)	Number of passes	Tensile shear strength (N/mm²)	Weld width (mm)	SN Ratio Strength	SN Ratio Width
1	25.5	300	70	1.622	1.721	4.201	-4.714
2	25.5	400	75	1.064	1.438	0.539	-3.157
3	25.5	500	80	1.251	0.554	1.945	5.125
4	27	300	75	2.043	1.685	6.205	-4.534
5	27	400	80	3.427	1.660	10.698	-4.404
6	27	500	70	1.982	2.576	5.942	-8.218
7	28.5	300	80	2.461	2.269	7.822	-7.115
8	28.5	400	70	2.272	2.041	7.128	-6.195
9	28.5	500	75	0.905	1.359	-0.867	-2.664

Smaller is better $SNs = -10 \log\left(\frac{1}{n}\sum_{i=1}^{n} y^2\right)$ (1)

Larger the better $SN_L = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y^2}\right)$ (2)

Nominal the better $SN_N = 10\log\left(\frac{Y^2}{s^2}\right)$ (3)

Where mean response $Y = \frac{1}{n}\sum_{i=1}^{n} y$

In this research, two quality characteristics were considered such as weld strength and weld seam width. These were optimized separately by Taguchi technique. Regression equation was established between control factors and responses and mean effect plot for S/N ratio of parameters. ANOVA table for the objectives were analyzed for both the experiment.

Fig. 3 (a) shows the mean effect plot for SN Ratios of weld strength which indicates effects of all the control parameters that are considered in the welding of natural polypropylene with black polypropylene specimens, this graph indicates that the laser power_1 (25.5W), scanning speed_1 (300mm/min) and number of passes_3 (25) are the optimized process parameters to obtain maximum weld strength. Similarly, Fig. 3 (b) shows the mean effect plot for SN Ratios of weld width, which indicates that the laser power_2 (27W), scanning speed_3 (500mm/min) and number of passes_1 (15) are the optimized process parameters to obtain minimum the weld seam width.

Fig. 4 (a) shows the mean effect plot for SN Ratios of weld strength which indicates effects of all the control parameters that are considered in the welding of natural polypropylene with jute fiber reinforced polypropylene specimens, this graph indicates that the laser power_2 (27W), scanning speed_2 (400mm/min) and number of passes_3 (80) are the optimized process parameters to obtain maximum weld strength. Similarly, Fig. 4 (b) shows the mean effect plot for SN Ratios of weld width, which indicates that the laser power_1 (25.5W), scanning speed_3 (500mm/min) and number of passes_3 (80) are the optimized process parameters to obtain minimum the weld seam width.

ANOVA for the response of weld strength and weld seam width for natural polypropylene with black polypropylene welded specimens was performed. It was found that all the factors have a significant effect on the response of weld strength. Scanning speed has the greater effect on the response. Scanning speed contributes about 47.18% on the weld strength. Whereas for response of weld width, it was found that all the factors have a significant effect on the response of weld width. Scanning speed has the greater effect on the weld width. Scanning speed contributes about 36.25% on the weld seam width. Later the regression analysis was carried out and a relationship was established between input parameters and response weld strength and weld width are given by Equation 5.4 and Equation 5.5 respectively.

Regression Equation

$$\text{Tensile shear strength (N/mm}^2\text{)} = (21.5 - 0.298\ \text{Power (W)} - 0.03491\ \text{Speed (mm/min)} + 0.606\ \text{Number of passes}) \quad (5.4)$$

$$\text{Weld width (mm)} = (-1.20 + 0.240\ \text{Power (W)} - 0.00813\ \text{Speed (mm/min)} + 0.1531\ \text{Number of passes}) \quad (5.5)$$

Similarly ANOVA for the response of weld strength and weld seam width for natural polypropylene with jute fiber reinforced polypropylene welded specimens was performed. It was found that all the factors have a significant effect on the response of weld strength. Laser power has the greater effect on the response. Laser power contributes about 41.2% on the weld strength. Whereas for weld width, it was found that all the factors have a significant effect on the response of weld width. Laser power has the greater effect on the response. Laser power contributes about 35.97% on the weld seam width. Later the regression analysis was carried out and a relationship was established between input parameters and response weld strength and weld width are given by Equation (5.6) and Equation 5.7.

Regression Equation

$$\text{Tensile shear strength (N/mm}^2\text{)} = (-5.04 + 0.189\ \text{Power (W)} - 0.00331\ \text{Speed (mm/min)} + 0.0421\ \text{Number of passes}) \quad (5.6)$$

$$\text{Weld width (mm)} = (1.26 + 0.217\ \text{Power (W)} - 0.00198\ \text{Speed (mm/min)} - 0.0618\ \text{Number of passes}) \quad (5.7)$$

3.2 Grey Relational Analysis

In this research work two response parameters are considered for the optimization. Optimization of multiple quality characteristics is more difficult and complicated than that of the single quality characteristics. Grey relational analysis is used to determine the single parametric combination that improves the performance of an overall process. In this method, the parameters are normalized in order to make it of one dimension and dimensions. The experiments are ranked based on increasing order of their grey relational grade (GRG). It is a concept to measure the degree of relation between parameters based on likeness and dissimilarity. Grey relational method is used to vary the two quality parameters to single quality parameter, so that multi objective is renewed into single objective for utilization. This is done by obtaining grey relation grade (GRG). Grey relation grade (GRG) is used as a performance characteristics in optimization technique and then by using Taguchi design, the optimal process parameters are determined using parameter design. Thus, it identifies the most influencing factors that affect the response. Hence grey relational analysis is considered as multi objective optimization technique to optimize the process parameters.

In grey relational analysis the higher the grey relational grade value, is closer to optimal value. Higher grey relational grade gives better multiple performance characteristic and comparative positions among machining parameters. The Table 5 and Table 6 shows the grey relational grades for natural polypropylene with carbon black induced polypropylene welded specimens and natural polypropylene with jute fiber reinforced polypropylene welded specimens respectively, arranged in an order from highest to lowest. The GRG for each level were calculated by taking the average of all the grey relational grade values for that specified parameter. The level having highest grey relational grade values are the optimized level. So with the help of response Table 7 for natural polypropylene with carbon black induced polypropylene welded specimens the optimal parameter combinations has been determined as laser power_2 (27W), scanning speed_1 (300mm/min) and number of passes_3 (25). From the response Table 8 for Natural Polypropylene with Jute Fiber Reinforced Polypropylene welded specimens the optimal parameter combinations has been determined as laser power_2 (27W), Scanning speed_2 (400mm/min) and Number of passes_3 (80).

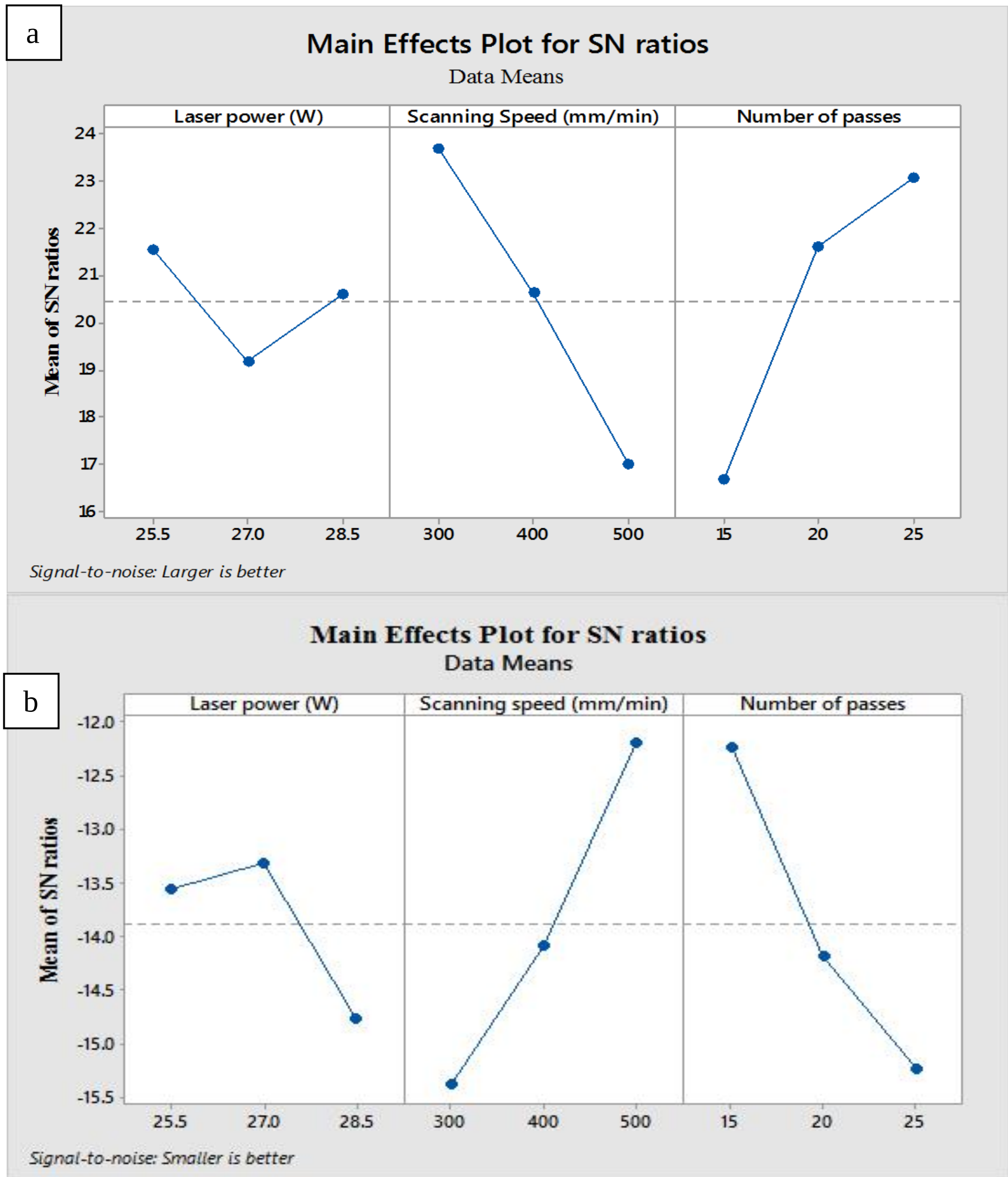

Fig -3: Variation of SN ratios of (a) weld strength (b) weld width values with controllable parameters for natural polypropylene with black polypropylene welded specimens

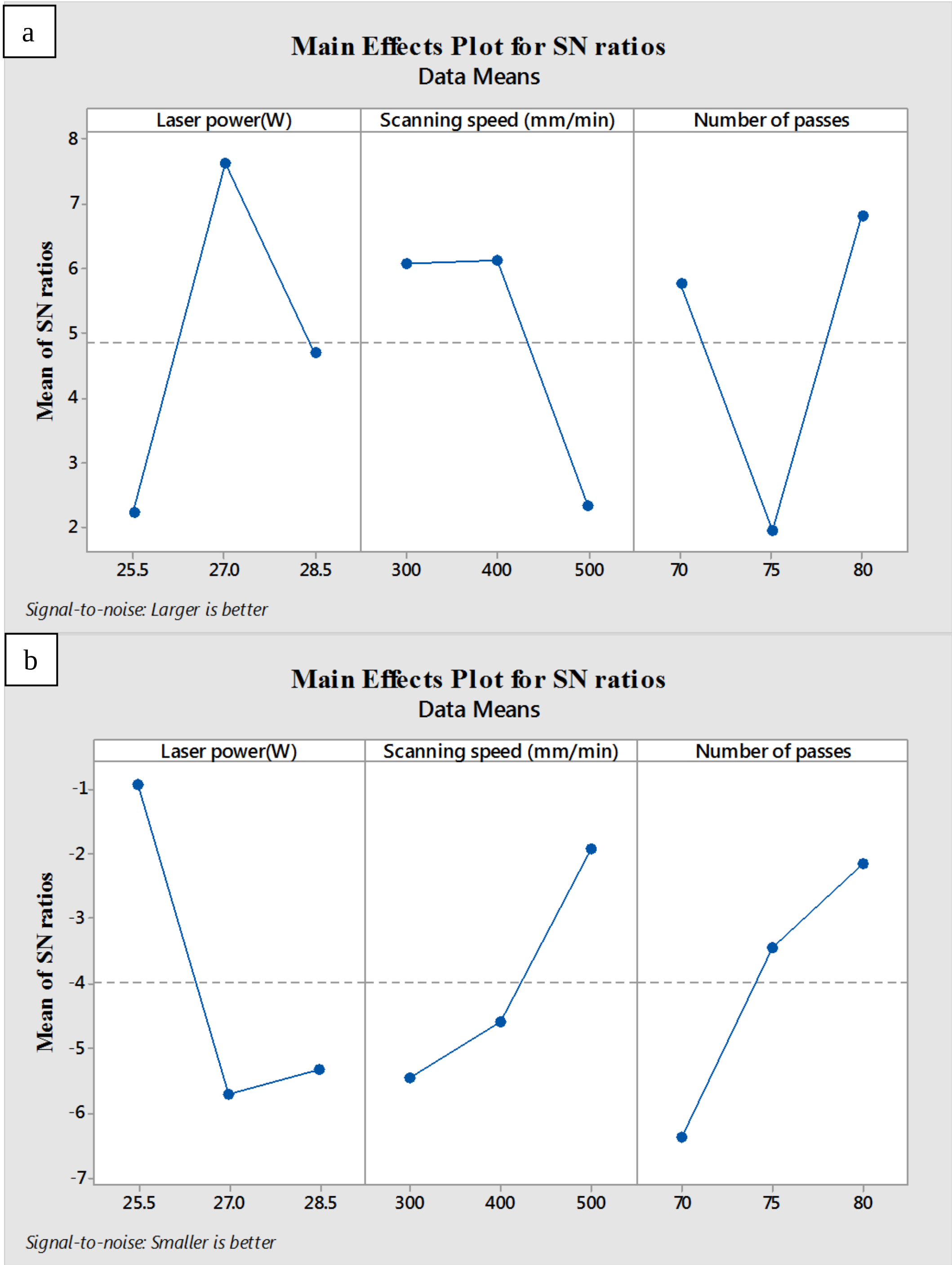

Fig -4: Variation of SN ratios of (a) weld strength (b) weld width values with controllable parameters for natural polypropylene with jute fiber reinforced polypropylene welded specimens

Table -5: Rank order according to grey relational grade for natural polypropylene with black polypropylene welded specimens

Exp. No	Laser power (W)	Scanning speed (mm/min)	Number of passes	GRG
4	27	300	20	0.673
6	27	500	15	0.667
5	27	400	25	0.625
7	28.5	300	25	0.601
1	25.5	300	15	0.580
2	25.5	400	20	0.531
3	25.5	500	25	0.519
9	28.5	500	20	0.468
8	28.5	400	15	0.438

Table -6: Rank order according to GRG for natural polypropylene with jute fiber reinforced polypropylene welded specimens

Exp. No	Laser power (W)	Scanning speed (mm/min)	Number of passes	GRG
5	27	400	80	0.739
3	25.5	500	80	0.683
4	27	300	75	0.474
7	28.5	300	80	0.469
8	28.5	400	70	0.463
9	28.5	500	75	0.445
2	25.5	400	75	0.441
1	25.5	300	70	0.438
6	27	500	70	0.400

Table -7: Response table for grey relational grade for natural polypropylene with black polypropylene welded specimens

Welding parameter	**Grey relation grade**		
	Level 1	**Level 2**	**Level 3**
Laser Power (P)	0.543	**0.655***	0.502
Scanning speed (SS)	**0.618***	0.531	0.551
Number of passes (N)	0.561	0.557	**0.581***

*Optimized values

Table -8: Response table for grey relational grade for natural polypropylene with jute fiber reinforced polypropylene welded specimens

Welding parameter	Grey relation grade		
	Level 1	Level 2	Level 3
Laser Power (P)	0.521	**0.538***	0.459
Scanning speed (SS)	0.460	**0.548***	0.509
Number of passes (N)	0.434	0.453	**0.630***

*Optimized values

3.3 Scanning Electron Microscopy (SEM)

Scanning Electron Microscopy micrographs of laser weld seam surface and cross sections were taken by using machine TESCAN-VEGA 3 5.0kV. The examinations of the SEM micrographs of weld seam surface and cross section are as follows.

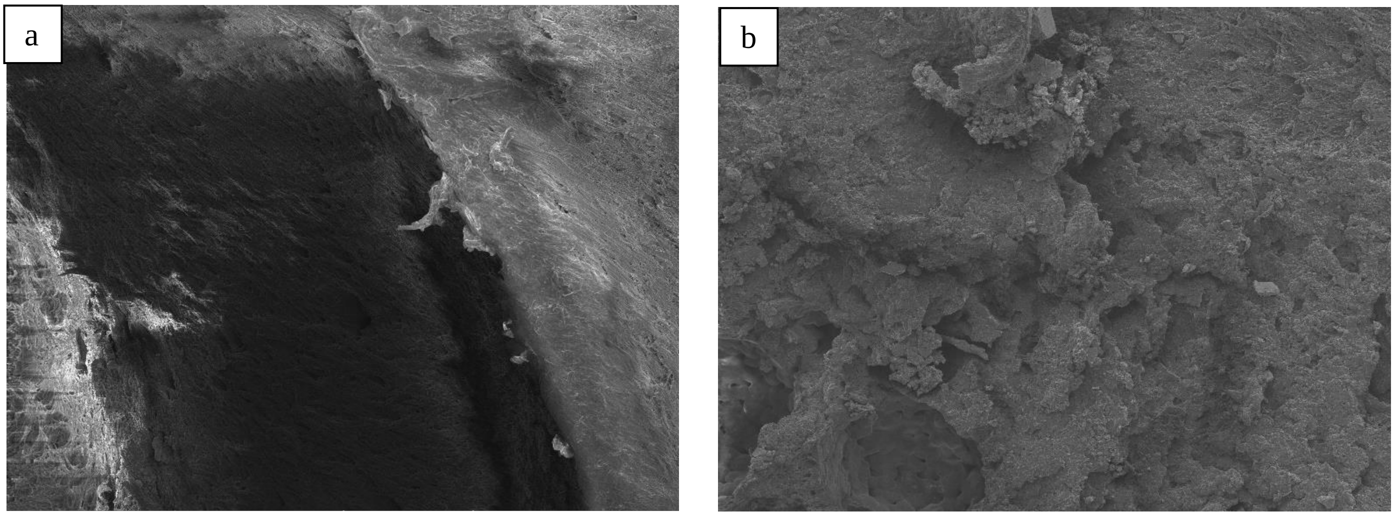

Fig -5: SEM of laser weld seam surface of natural polypropylene with carbon black induced polypropylene welded specimens (a) Fourth specimen transparent part (b) Fifth specimen opaque part

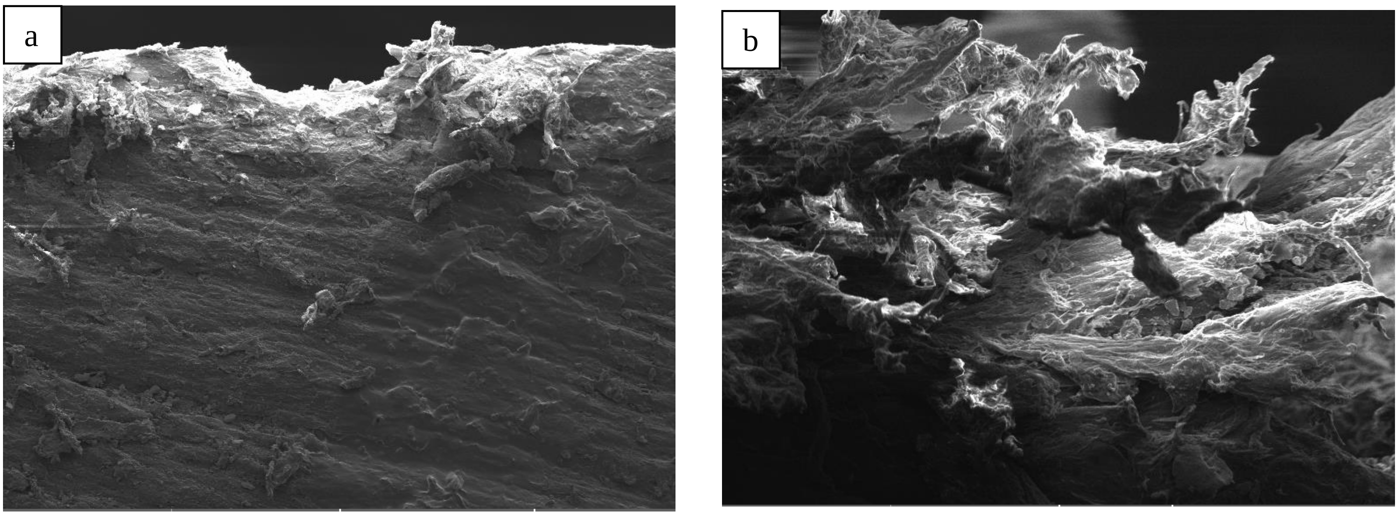

Fig -6: SEM of laser weld seam cross section of natural polypropylene with carbon black induced polypropylene welded specimens (a) Third specimen opaque part (b) Fifth specimen opaque part

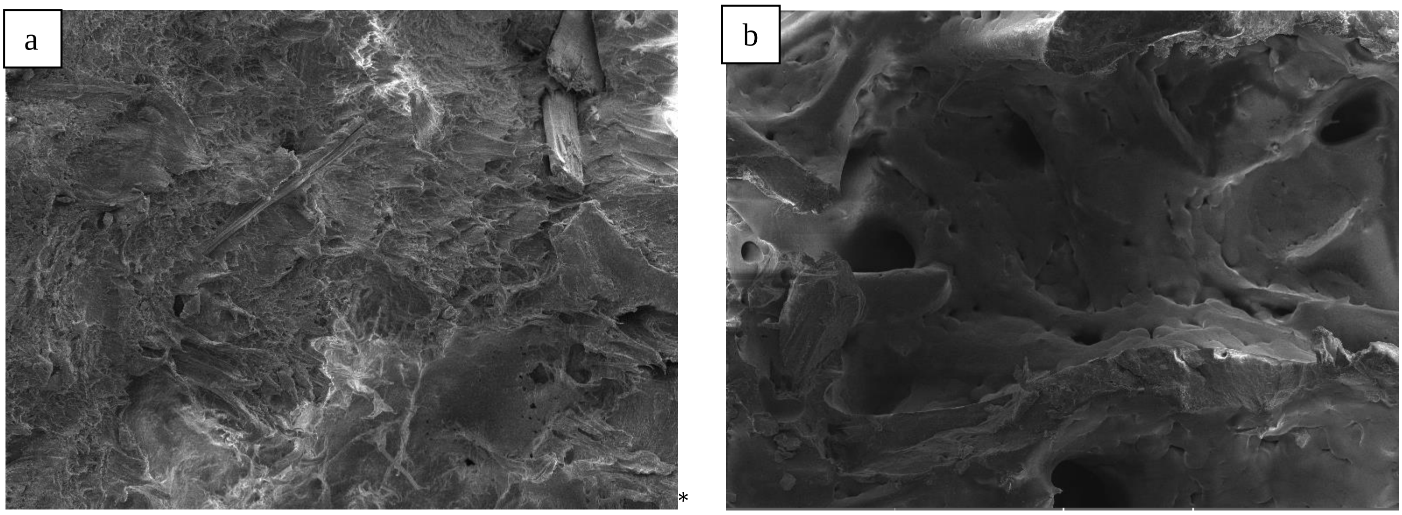

Fig -7: SEM of laser weld seam surface section of natural polypropylene with jute fiber reinforced polypropylene welded specimens (a) First specimen opaque part (b) Fourth specimen transparent part

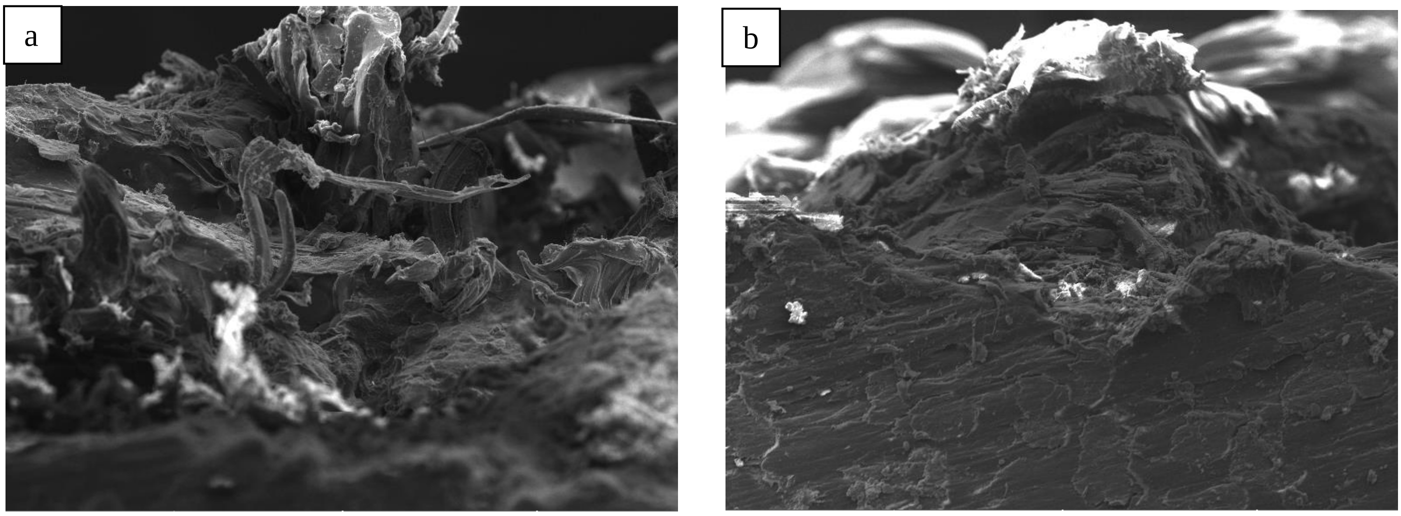

Fig -8: SEM of laser weld seam cross section of natural polypropylene with jute fiber reinforced polypropylene welded specimens (a) Seventh specimen opaque part (b) Ninth specimen transparent part

Fig. 5 (a), (b) and Fig. 6 (a), (b) shows the SEM of weld seam surface and weld cross section for the natural polypropylene with carbon black induced polypropylene welded specimens respectively. Fig. 7 (a), (b) and Fig. 8 (a), (b) shows the SEM of weld seam surface and weld cross section for the natural polypropylene with jute fiber reinforced polypropylene welded specimens respectively. In the SEM images of natural polypropylene it is observed that there are small cracks formed in the material and in the opaque part the dilution of material is observed. All the SEM images show that if the scanning speed and number of passes are more dilution of material can be seen. In the specimens having more weld strength, more dilution of material has been observed. When the images of natural polypropylene with carbon black induced polypropylene welded joints and images of natural polypropylene with jute fiber reinforced polypropylene welded joints are compared in the jute fiber material dilution is very less and strength is also less. The jute fiber reinforced material is not completely melted as the carbon black induced polypropylene hence more strength was found in the natural polypropylene with carbon black induced polypropylene welded joints. SEM analysis shows that, higher the strength of joint results in maximum damage on specimen and if the scanning speed and number of passes are more, more dilution of material can be seen. The dilution of material in jute fiber reinforced specimens is less as compared to carbon black specimens. In jute fiber specimen fiber pull out was observed during SEM.

4. CONCLUSIONS

In this research work, Taguchi method along with ANOVA and grey relational analysis is used to determine the effects of laser transmission welding process parameters on the laser lap welded joints of natural polypropylene with black polypropylene and natural polypropylene with jute fiber reinforced polypropylene. Taguchi method is used as single objective optimization technique to optimize process parameters considering individual quality characteristics and grey relational analysis is used as multi objective optimization technique to optimize process parameters considering both quality characteristics simultaneously. The influence and percentage contribution of each process parameter on weld quality is identified and studied quantitatively using ANOVA technique. To study surface morphology and cross sections of weld seam SEM micrographs are used.

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