Parametric Study of Laser Welding on Polyamide using Design of Experiments

Girish Kumar R1, H N Narasimha Murthy2, B Anand3 and Syed Jabiulla4
1 Assistant Professor, Dept. of Mechanical Engineering, RV College of Engineering, Bengaluru
2 Professor, Dept. of Mechanical Engineering, RV College of Engineering, Bengaluru
3 Professor, Dept. of Mechanical Engineering, RV College of Engineering, Bengaluru
4 Research scholar, Dept. of Mechanical Engineering, RV College of Engineering, Bengaluru

Email: girishkumarr@rvce.edu.in

Abstract. Laser welding was primarily employed for metals but recent developments in laser technology have enabled its applications in the polymers field. Laser transmission welding or joining of two polymers and metal-polymer has become feasible. The study was mainly aimed to investigate the influence of laser power, speed of welding, and number of passes based on Taguchi orthogonal array on responses by using continuous mode high power diode fiber laser on polyamide. The weld quality was assessed by measuring the strength of weld and width of the weld seam. Initial study on diode fiber laser welding machine and the parameters associated with it was essential to design the experimental layout. Polyamide, which is widely used in the automotive industry was selected as the material and the influence of various parameters on the laser welds were studied using design of experiments. The experimental studies were performed based on orthogonal array method. The responses of the weld were measured using an optical metallurgical microscope. The ideal parameters for maximum joint strength and minimum weld width are investigated using Taguchi method. The multi-objective optimization has been done by applying grey relational analysis to identify the levels of factors that result in the maximum strength and minimum weld seam width.

Keywords: Laser transmission welding, Diode laser, Polyamide, Design of experiments

1. Introduction
The constantly expanding interest in plastic merchandise and the spread utilization in high-tech fields and regular life from automotive enterprises to nourishment and medicinal item bundles, materials, or structural designing. In the joining of thermoplastic components, a major challenge is to reduce the failure of joints in industrial applications. The current techniques of joining thermoplastics such as friction welding, ultrasonic welding, and hot plate welding for joining of thermoplastic is still time-consuming and less accurate. Therefore, laser welding is considered as a viable method of joining the thermoplastics. The laser system consists a manageable beam power which reduces the risk of damage to specimens, exact focusing of the laser beam which allows accurate joints, and a non-contact, clean and speedy process. Laser transmission welding is creative plastic combination advancement with clearly comprehended normal purposes of laser material processing, as a non-contact, adaptable procedure, simple to control and mechanized Taguchi strategy is a precise use to outline and examination of analyses with the end goal of planning and enhancing item quality. The improvement of one specific quality characteristic could possibly lead to thoughtful degradation of the other crucial quality characteristics [1-3].

The applications of laser welding have been commendable even in the field of medical sciences where thermoplastics implants have been joined with the help of lasers. Transparent thermoplastics can
also be welded by adding additives to them during the production stage. The filler materials will ensure that the energy-containing laser beams do not reflect, causing haphazard heat dissipation on undesired locations. Laser welding has evolved so sophisticatedly that today there is research happening on Artificial Intelligence related to laser welding real-time monitoring [4-5]. Lasers of different energy sources have been studied to suit different materials. Lasers that suit metals may not exactly give desirable results when used on plastics. Hence, laser selection to weld a particular material plays a prominent role in the results. Computer-controlled simulations have helped in validating the behavior of the laser beam and the results as well. Tools like ANSYS and ABAQUS are used for analyzing the experimental results. The possible responses to the laser experiments have also been investigated in detail in many studies which have given us clarity on the source of the laser to be used and also the responses to be selected [6-13].

In laser transmission welding (LTW) the samples to be joined are brought into direct contact before welding as shown in Figure 1. Two thermoplastic materials are needed for the welding process, which allow different degrees of laser energy transmission. The part at the laser wavelength which optically transparent (A, which is natural, or colored with non-absorbing pigment) is brought in contact with a part that is optically dense (B, colored with an absorbing pigment). The beam of laser is transmitted through part A, losing minimum energy, and is completely absorbed within the surface or interfacial layer of part B. The direct contact between the two parts results in the heating of part A at the joint interface. Welding occurs due to melting and fusion of the 2 both materials at the interface. For laser transmission welding (LTW), it is crucial to achieve consistent and sufficient heating of the thermoplastic in the joint region during pre-, melt, and fusion phases resulting in consistent thickness for the weld. Different processing parameters and thermoplastic properties influence the quality of weld for a given power of laser [5]. Compared to thermoplastics which were extensively studied like ABS, PLA, and PMMA, Polyamide was not exposed to such studies. Polyamide has many applications in automotive industries hence this material can be used for research. Polyamide possesses great strength and durability hence the power required is more compared to other thermoplastics hence this material was not used for this technique extensively. For this reason, a continuous mode high power Diode Fiber Laser was used as the laser source.

In this present research, the Taguchi method was used to streamline the laser transmission welding method by considering the weld seam width. At this point, the determination of laser transmission welding procedure parameters and the assessment of weld qualities were examined. After that, the ideal process parameters with the help of multiple quality characteristics were obtained.
2. Experimentation

2.1. Materials selected for welding
Recent developments in laser technology have enabled the welding of different plastics or thermoplastics like ABS, COC, PC, and other thermoplastics. In this paper, polyamide is used as the specimen to study the effect of laser parameters. Polyamides are widely used in the applications of bearing, bushing, gears, rollers, wheels, wear plates, and more. Polyamide has high mechanical strength, high mechanical damping ability, outstanding fatigue resistance, high impact & shock resistance, exceptional wear resistance and corrosion resistance, especially in dirty environments. A polyamide sheet was machined into 85 mm length, 30 mm width, and 3mm thickness different blocks. The welding process was carried between two polyamides one being the transmission part, and other, absorbent part. Black coloured polyamide was used as the absorbent part. Figure 2 shows the specimens readied for the laser welding operation.

![Figure 2. Polyamide specimens for welding](image)

2.2. Experimental Setup
The plates of polyamide, one opaque and the other transparent (white) of 85mm × 35mm, and thickness 3mm are placed over each other to make a lap joint. The location angle is 90 degrees. A higher power 6 axis diode laser with 2.55 mm range was used for the welding of the parts. Contactless temperature measurement along with fast power controllability to minimize thermal damage make the diode laser a perfect tool for these types of applications. The wavelength range of the diode laser was 940-1060 nm and 600-1000-micron fiber range. The laser used had a capability of 2 beam delivery. In order to study the laser transmission welding of polyamide, different equipment parameters, specimen parameters, and process parameters were discussed and these were evaluated. Process parameters selected were laser power, scanning speed (welding speed), and number of passes. Standoff distance (distance between the source of laser and the specimen) was maintained constant at 290 mm. Shear tensile strength and weld width were considered as response parameters. A UTM was used for shear tensile tests and a Travelling Microscope was used for, carefully measuring the weld width after the destructive tests. Table 2 shows the experimental plan by numbers and also their respective responses.
3. Methodology employed
Using Minitab 16, an L9 orthogonal array was selected as the basis for the experimental study. This meant that a total of 9 experiments need to be carried out with predefined combinations of process parameters (power, scanning speed, and number of passes). This experimental set has been tabulated as shown in Table 1. The table shows each of the machine parameters and their chosen levels for the experiments. Figure 3 shows the methodology followed to achieve the experimental results.

![Diagram](image)

**Figure 3.** Methodology adopted for the study

### Table 1. Process parameters and levels (Layout design)

| Factors               | Level - 1 | Level - 2 | Level - 3 |
|-----------------------|-----------|-----------|-----------|
| Power (W)             | 200       | 210       | 220       |
| Welding speed (mm/sec)| 190       | 195       | 200       |
| Number of passes      | 2         | 3         | 4         |

4. Results and discussions
The process of laser welding was carried out employing the design of experiments (DOE) and 9 level orthogonal arrays. Varying different levels of power, scanning speed, and number of passes the effects of transmission welding were investigated. Different levels of power with different levels of speed and number of passes were combined and permuted. All the specimens were welded according to the DOE and the weld strength and weld width were calculated to investigate the optimum parameters required for welding of polyamide as shown in Table 2.
## Table 2. Experimental Results

| Experiment Number | Power (W) | Scanning speed (mm/s) | Number of passes | Shear Strength (N/mm²) | Weld width (mm) |
|-------------------|-----------|-----------------------|------------------|------------------------|-----------------|
| A1                | 200       | 190                   | 2                | 6.8                    | 3.42            |
| A2                | 200       | 195                   | 3                | 7.2                    | 4.79            |
| A3                | 200       | 200                   | 4                | 6.9                    | 3.49            |
| B1                | 210       | 190                   | 3                | 6.7                    | 2.79            |
| B2                | 210       | 195                   | 4                | 8.1                    | 3.52            |
| B3                | 210       | 200                   | 2                | 7.2                    | 2.38            |
| C1                | 220       | 190                   | 4                | 7.6                    | 3.22            |
| C2                | 220       | 195                   | 2                | 11.9                   | 3.32            |
| C3                | 220       | 200                   | 3                | 7.1                    | 2.69            |

4.1. Analysis of Probability plots

### 4.1.1. Analysis of Probability Plot for Weld Strength

The normal probability plot for S/N ratios of weld strength is shown in Figure 4. From the experiment, the weld joint strength results were found to be lying close to the trend line of the plot of normal probability which shows that the entire process was carried out at a stable atmosphere and hence no individual factor affected the outcome of the results.

### 4.1.2. Analysis of Probability Plots for Weld Seam Width

The normal probability plot for S/N ratios for the width of the weld is shown in Figure 5. From the study, the weld seam width result was found to be lying close to the trend line of the normal probability plot which indicates that the whole process was carried out at stable conditions and hence no individual factor influenced the outcome of the results.

![Probability Plot of shear strength](image)

**Figure 4.** Probability plot for weld strength
To explore the effect of each factor on the output, the signal-to-noise ratio (SN) needed to be considered for each experiment conducted. To calculate the S/N ratio, there were 3 methods used based on which SN ratios were calculated. They are, the smaller the better, the larger the better, and nominal the best. Each of these procedures was considered depending on the characteristics of the response values. Table 3 illustrates the values of signal-to-noise ratio for each experiment.

### Table 3. SN ratio with corresponding factor combinations

| Experiment Number | Power (W) | Scanning speed (mm/s) | Number of passes | Shear Strength (N/mm²) | Weld width (mm) | SNRA1  | SNRA2  |
|-------------------|-----------|-----------------------|------------------|------------------------|----------------|--------|--------|
| A1                | 200       | 190                   | 2                | 6.8                    | 3.42           | 16.6502 | -10.6805 |
| A2                | 200       | 195                   | 3                | 7.2                    | 4.79           | 17.1466 | -13.6067 |
| A3                | 200       | 200                   | 4                | 6.9                    | 3.49           | 16.7770 | -10.8565 |
| B1                | 210       | 190                   | 3                | 6.7                    | 2.79           | 16.5215 | -8.9121  |
| B2                | 210       | 195                   | 4                | 8.1                    | 3.52           | 18.1697 | -10.9309 |
| B3                | 210       | 200                   | 2                | 7.2                    | 2.38           | 17.1466 | -7.5315  |
| C1                | 220       | 190                   | 4                | 7.6                    | 3.22           | 17.6163 | -10.1571 |
| C2                | 220       | 195                   | 2                | 11.9                   | 3.32           | 21.5109 | -10.4228 |
| C3                | 220       | 200                   | 3                | 7.1                    | 2.69           | 17.0252 | -8.5950  |

#### 4.2.1. Single Objective Optimization Technique

In this project, 2 response characteristics which are weld joint strength and weld seam width were considered. Using Taguchi technique, both the characteristics were analyzed separately. The main effect plot for shear strength and weld width were plotted and the Regression Equation was established for both parameters. ANOVA table is illustrated and analyzed for both the objectives.
4.2.2. ANOVA for Weld Strength

ANOVA for weld joint strength shown in Table 4 related to weld strength was conducted and it was noticed that all the parameters have a notable influence on weld strength. Scanning speed was the most significant factor as a percentage of contribution for determining weld strength. R-sq value of 87.11% confirmed the reliability of the experiment.

Table 4. Analysis of Variance for S/N ratios of weld strength

| Factors        | DF | SS    | MS    | F     | P     | % Contribution |
|----------------|----|-------|-------|-------|-------|----------------|
| Power          | 2  | 6.096 | 3.048 | 2.24  | 0.309 | 28.87          |
| Scanning speed | 2  | 8.136 | 4.068 | 2.99  | 0.251 | 38.53          |
| Number of passes | 2  | 4.162 | 2.081 | 1.53  | 0.395 | 19.71          |
| Error          | 2  | 2.722 | 1.36  |       |       | 12.89          |
| Total          | 8  | 21.116|       |       |       | 100            |

4.2.3. ANOVA for Weld Width

ANOVA for S/N ratios shown in Table 5 related to weld width was conducted and it was observed that all the parameters had a significant outcome on weld seam width. Power was the most significant factor with 45.14% of the contribution for determining weld width. R-sq value of 96.49% ascertains the reliability of the study.

Table 5. Analysis of Variance for S/N ratios of weld width

| Factors        | DF | SS    | MS    | F     | P     | % Contribution |
|----------------|----|-------|-------|-------|-------|----------------|
| Power          | 2  | 1.717 | 0.858 | 12.85 | 0.072 | 45.14          |
| Scanning speed | 2  | 1.669 | 0.834 | 12.49 | 0.074 | 43.88          |
| Number of passes | 2  | 0.284 | 0.142 | 2.13  | 0.320 | 7.47           |
| Error          | 2  | 0.133 | 0.066 |       |       | 3.51           |
| Total          | 8  | 3.803 |       |       |       | 100            |

4.2.4. D. Multi-objective Optimization Technique

For optimization, as 2 response parameters were considered, a multi-objective optimization technique was adopted. In this project, Grey Taguchi methodology for optimizing process parameters was implemented. In stage 1, the Grey relational technique was used to determine the grade, based on which it was optimized by Taguchi technique. The grey relation rank for each specimen was obtained and illustrated in Table 6.

It is evident from the table that specimen C2 had been valued with the highest grey relation grade with parameters: Power 220 Watts, scanning speed 195 mm/s, and number of passes 2. Specimen A2 recorded the lowest grey relation grade and rank.
### Table 6. Gray relation rank

| Exp no. | Power in Watts | Scanning speed mm/s | Number of passes | Grey Relation Grade | Rank |
|---------|----------------|---------------------|------------------|---------------------|------|
| C2      | 220            | 195                 | 2                | 0.780               | 1    |
| B3      | 210            | 200                 | 2                | 0.678               | 2    |
| C3      | 220            | 200                 | 3                | 0.573               | 3    |
| B1      | 210            | 190                 | 3                | 0.539               | 4    |
| C1      | 220            | 190                 | 4                | 0.483               | 5    |
| B2      | 210            | 195                 | 4                | 0.460               | 6    |
| A1      | 200            | 190                 | 2                | 0.437               | 7    |
| A3      | 200            | 200                 | 4                | 0.431               | 8    |
| A2      | 200            | 195                 | 3                | 0.344               | 9    |

4.2.5. Validation of Results

The optimum parameters obtained from grey relation analysis was considered as the base for validation of the result. Specimen C2 with parameters Power 220 W, scanning speed 195 mm/s, and number of passes 2 was selected. The polyamide specimen was welded again using the same optimized parameters to confirm the result obtained through analysis. The results of the validation are compared with the prior results obtained through analysis and the percentage error is tabulated as shown in table 7.

### Table 7. Validation of result

| Specimen     | Shear strength (N/mm²) | Weld width (mm) |
|--------------|------------------------|-----------------|
| Actual specimen | 11.9                  | 3.32            |
| Experimental Specimen | 10.2                  | 3.75            |
| % error      | 14.28 %                | 12.95%          |

The experiment was carried on the new specimen with parameters Power 220 W, scanning speed 195 mm/s and number of passes 2. The shear strength of the experimented polyamide was 10.2 N/mm² compared to 11.9 N/mm² of actual specimen and the percent error calculated was 14.28 %. The specimens after destructive testing are shown in Fig 6. Similarly Weld width obtained was 3.75 mm compared to 3.32mm of actual specimen whereas the percent error calculated was 12.95%.

From the result table it is evident that the parameters selected are optimum with minimum percent error. Hence the results obtained are validated and can be confirmed.
5. Conclusion
In the present work, lap welding of two Polyamide plastic plates each of 3 mm thickness – one being transparent and the other opaque, were welded under different conditions of welding, by laser transmission welding. Polyamide has been hardly used for laser welding experiments as only low power lasers are generally used for plastic materials. Based on previous studies, an L9 orthogonal array was designed by considering laser power, scanning speed, and number of passes. The response parameters were set as shear tensile strength and weld seam width. The effects of process parameters including power, scanning speed, and number of passes on the width of the weld seam and the joint strength were identified and analysed. ANOVA showed that scanning speed and power were the most influencing factors for maximum weld shear strength and minimum weld seam width respectively. Percentage contribution of power, scanning speed, and number of passes 28.7%, 38.53%, and 19.71% respectively for maximum weld strength. Percentage contribution of power, scanning speed, and number of passes was 45.14, 43.88 %, and 7.47% respectively for minimum weld width. In single-objective optimization, it was found that the optimum parametric condition for maximum joint strength was found to be P3 SS2 NOP1 (Power: 220 W, scanning speed: 195 mm/s, and number of passes: 2). For minimum weld seam width, the optimum condition was P1 SS2 NOP2 (Power: 200 W, scanning speed: 195 mm/s, and number of passes: 3). Single-objective optimization was done using Taguchi method. Multi-objective optimization was carried out through Grey-Taguchi method. The optimum parametric condition for maximum joint strength and minimum weld seam width simultaneously was P3 SS2 NOP1 (Power: 220 W, Scanning speed: 200 mm/s, and number of passes: 2).

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