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OPTIMIZATION OF LASER WELDING PARAMETERS FOR JOINING OF POLYLACTIC ACID SHEETS USING FEM

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Abstract

The Plastic market has been increasing exponentially day by day as the plastic utility expanded to various other fields like automotive industry, medical industry, food packaging industry etc. The value of the plastics market is projected to reach USD 721.14 billion by 2025, expanding at a CAGR of 4.0 percent over the forecast period. In instance, the market size for polylactic acid (PLA) was expected to be 950.7 million USD in the year 2017. The most significant benefit of polylactic acid is that it is naturally biodegradable, it is produced from renewable sources, and it has qualities that are on par with or even superior to those of plastics derived from petroleum.

Laser welding is preferred over other methods because of its industrial applications. Also, the processing time is very less when compared to other methods and the filler material is not required for laser welding. Thus, the joint finish will be fair in addition to achieving good strength.

Ample research has been going on in the field of laser technologies and joining of polymers using Lasers. There are but few research work done joining (Lap joint) poly lactic acid using laser welding technology. The main objective of this work is is to optimize the process parameters of laser welding, finding the weld strength and the residual stresses. PLA sheets with dimensions of 80*35*4 were 3D printed using FDM method. These specimens are welded as per the design of experiments adopted. The specimens with spacers are tested experimentally using tensometer for determining the weld strength and optical metallurgical microscope to find the weld width. FEM analysis has been carried out using ANSYS 18.1 with the same set of parameters used for the experimentation. The optimization has been done on the basis of experimental as well as the FEM Analysis.

Keywords: Laser welding, laser welding of polymers, PLA, Polylactic acid, FEA

1.1 Introduction

The use of plastic in other industries, such as the automotive, medical, and food packaging sectors, has caused the plastic market to grow tremendously every day. By 2025, the plastics market is projected to be worth USD 721.14 billion, growing at a CAGR of 4.0%. Particularly, the market for Poly lactic acid (PLA) was expected to be worth USD 950.7 million in 2017. For various applications, these plastics can be joined using a variety of techniques. Solvent bonding, vibration welding, friction welding, ultrasonic welding, and laser welding are some of the more common techniques. Because of its industrial applications, laser welding is chosen over other methods.

Laser light can be utilised for joining thermoplastics in dualistic modes; i) by melting the exterior skin of a work piece and joining by merging which is commonly known as Butt joint and ii) by passing a laser light through a laser translucent work piece and joining at the mating surface of the former with a laser-absorbing work piece placed below it known as Lap joint.

1.2 Problem Area

The connecting of thermoplastic components presents a number of challenges, one of the most significant of which is lowering the failure rate of joints in industrial applications. The existing methods of combining thermoplastics, such as friction welding, ultrasonic welding, and hot plate welding, are still time consuming and less precise [1]. Other methods of joining thermoplastics include laser welding and ultrasonic welding. As a result of this, laser welding is taken into consideration to be a potential approach for combining the thermoplastics. The laser system has a controllable beam power, which lowers the likelihood that specimens will be damaged, precise focussing of the laser beam, which enables correct joints, and a non-contact, clean, and rapid procedure [2]. The main task was to get high strength of weld and low weld seam width. In order to incorporate this, the performances have to be improved to meet the requirement [3]. There are different types of thermoplastics which can be welded, among them PLA (Polylactic acid); on which lesser research was done with respect to laser welding was considered [4].

1.3 Literature Review

Deposition or plating of thin metallic foils was the method of investigation that S. Kannan and colleagues [5] used. For the purposes of this research, the additive manufacturing technique known as fused deposition modelling (FDM) was selected for usage, and the thermoplastic material of choice was ABS. Nickel layers of varied thickness were applied to ABS test samples and coated with nickel (10 microns to 100 microns). After electroplating, it was discovered that, with characterization tests such as tensile and flexural strength in both uncoated and coated condition, the tensile strength of coated specimen was 47% more than that of uncoated specimens, and the flexural strength of coated specimen has doubled to that of uncoated one. This was the case with coated specimens undergoing characterization tests in both uncoated and coated condition.

V. Wippo and colleagues [7] looked at the possibility of using laser transmission welding to combine fiber-reinforced thermoplastics. The joining was done with a diode laser, and an infrared camera was utilised to keep an eye on how it was going. There was an investigation on the temperature distributions. Within the context of the laser transmission welding method, V. Mamuschkin and colleagues [9] investigated the wavelength of a laser by taking into account the optical characteristics of the polymer. In the course of the experiment, a diode laser with a wavelength of 1530 nm was utilised. The feed rate was maintained at a constant of 1000 millimetres per minute. Each of the connecting partners has a thickness of 1 millimetre and contains 2% titanium dioxide. The computed intensity distribution served as the basis for the discovery of the temperature distribution. Yasuo Kurosaki and colleagues [10] conducted research on a novel fibre laser transmission welding approach for the construction of polymer components. With the assistance of a solid sink transparency, the researchers were able to avoid thermal damage at the surface of the component. The unique welding technique that makes use of fibre laser causes non-thermal damage on the surfaces of four different types of plastics (PC, PA6, PP, and PVC), all of which are often used in the process of assembling various pieces of medical equipment and other devices. L. Research on new generations of high power fibre lasers was conducted by Quintino et al. [11]. Using a fibre laser with 8 kW of power, welding was performed on API 5L: X100 pipeline steel. An examination of the weld profile geometry and an investigation of the transition between conduction and deep penetration welding modes were carried out.

Negin Amanat et al [6] examined the impact of laser power, welding velocity, and material morphology on the joint quality of poly-ether–ether–ketone (PEEK) utilising laser transmission welding. Two laser forces (10 and 20 W) and five output speeds (4, 8, 16, 32, 64 mm/s) were analysed. The outcomes demonstrated that the best joint qualities were accomplished by utilising the welding rate of 4 mm/s and 8 mm/s ranging from 22 to 25 Mpa. **J.P. Coelho** et al [1] studied a high speed (20 ms^{-1}) welding process using CO_2 laser on polypropylene and polyethylene. The dimension of weld seam and weld strength were analysed. The strength of the weld was achieved more than 90% for high-density polyethylene at speeds of 10 ms^{-1}.

In order to conduct an investigation on the laser contour welding process of polycarbonate, Bappa Acherjee and his colleagues [8] employed techniques such as finite element analysis (FEA) and design of experiments

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(DOE). To get numerical results, ANSYS was used, and the results were analysed. The objective of the sensitivity analysis was to identify the many channels via which the variables under investigation are influenced by the factors that are independent from the study. Power, welding speed, and beam diameter are all regarded to be independent variables, but the maximum temperature at the weld interface, weld breadth, and weld depths in both transparent and absorbent polymers are considered to be dependent factors. Even if the trend is the contrary for welding speed, the sensitivity of the weld width (WW) to changes in power is greater than that of the molten depths (DT and DA). The quantity of carbon black had a more significant influence on WW than both DT and DA put together. During the duration of the examination, the temperature rose to a maximum of 8300 degrees Celsius at its highest point.

1.4 Research Gap

Review of literature [1-6] on laser welding of thermoplastics indicated that most of the research has been focused on PP, PMMA, ABS and so on. Laser welding of polylactic acid (PLA) is scarcely reported. Review on laser welding parameters showed that welding speed, laser power and stand-off distance were most influencing parameters on weld quality. Also it was concluded based on review of optimisation techniques that Taguchi and Grey Relational Analysis were the most preferred optimisation techniques with respect to weld strength and weld width, the preferred responses for evaluating laser weld quality.

Review of literature [7-11] revealed that laser welding of polymers is studied considering Polycarbonate, PMMA, HDPE, etc. Parametric influence of laser machine and material parameters are studied. Many of the authors adopted fibre and diode lasers because of the controllability of laser parameters and ease of maintenance. There hasn't been a lot of study done on laser welding of several types of polymers like polypropylene and ABS, polylactic acid and ABS, or polyamide 6 and PLA. Experimentation makes up the vast majority of the research being done on laser welding of various polymers. In order to provide accurate predictions about temperature distribution and the geometry of molten pools, three-dimensional finite element models are built. Welding Processes can be simulated using FEA to propose optimal machine parameters establishing clear relationships between them and response factors.

2.1 Objectives

The following goals were chosen for the research based on a survey of the literature on laser welding of polymers:

1. 1. The purpose of this study was to investigate the effects of laser welding parameters on Poly-lactic Acid polymer reactions, tensile strength, and weld seam width using Taguchi orthogonal arrays for power, welding speed, and stand-off distance; specifically, the goal was to establish the relative importance of the input factors on the weld width and joint strength.
2. The S/N ratio and an analysis of the impacts of the process parameters were utilised in conjunction with Grey Relational Analysis to determine the ideal set of parameters for the weld strength and weld seam width of PLA joints, respectively. This was accomplished by using the S/N ratio as a guide.
3. By simulating the laser welding process of PLA joints using a moving heat source and analysing the reaction, the tensile stress of PLA joints is determined according to Taguchi orthogonal array.
4. To find the ideal set of parameters for the reaction tensile stress of PLA joints, laser welding settings on PLA joints were optimised.
5. The experimental study findings are used to validate the FEA results in order to compare the error % between the two studies and assure the improvement of optimum process parameters and the distinction between the theoretical (ideal) and practical approaches to laser welding PLA polymers.

2.2 Research Methodology

After doing an immense study of literature survey on laser welding of thermoplastics and thermoplastic materials used in welding process, process parameters, standards of specimen, the process procedure was formed. The fabrication of the polylactic acid (PLA) – a biodegradable thermoplastic was done by using fused deposition modelling with the dimension 80*35*4 mm. The specimens were fabricated in two sets of plates

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that were opaque and translucent. Design of Experiments (DOE) was applied using MINITAB, statistical software considered three factors, each at three variability levels using different levels of power, scanning speed and standoff distance. The selected parameter-levels resulted in a L9 orthogonal array.

By using AGILE laser system machine and fibre laser as a source, welding was done on specimens. Before testing to the strength of weld, the plates of dimension of 35*30*4 mm, the spacer was pasted on either side using epoxy resin to make a proper alignment of specimen to centerline for testing on tensile testing machines. Signal to Noise ratio (S/N ratio) analysis was carried out to study the effects of process parameters using the grey taguchi method.

Grey relation analysis was considered to find the optimised parameter. Figure 2.1 shows the flow of work in this research.

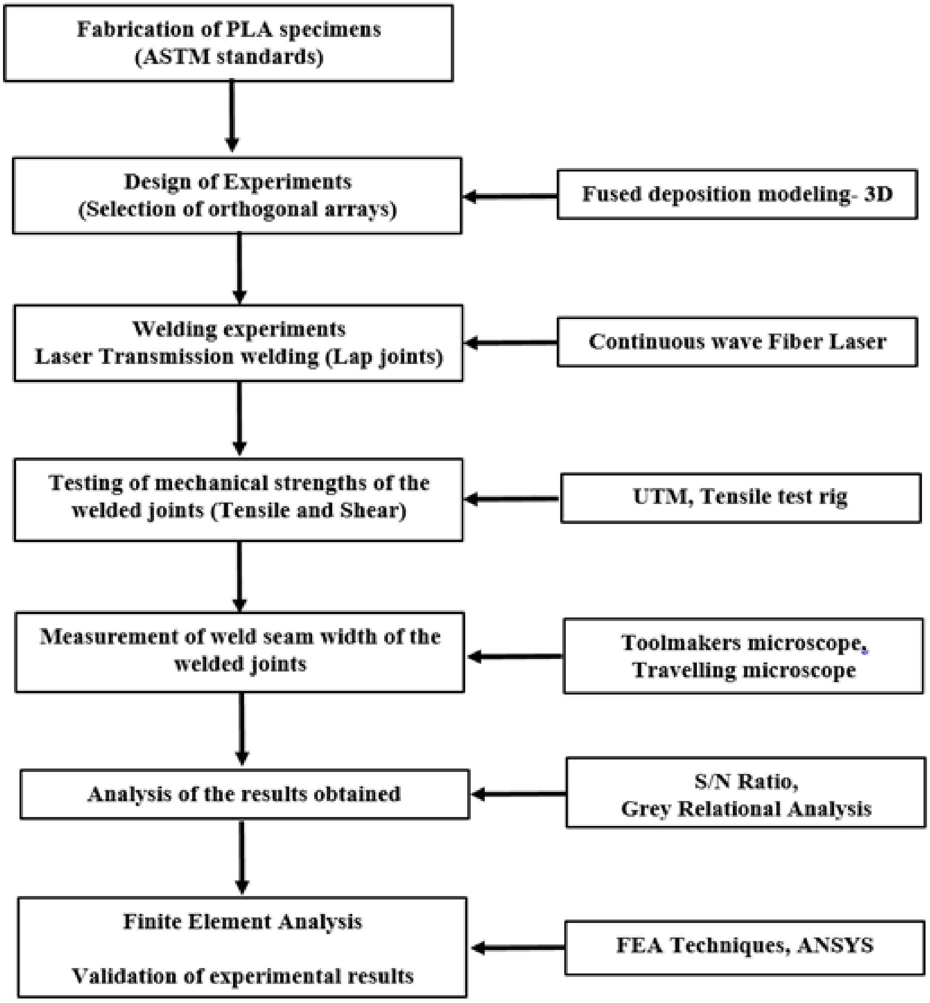

Fig 2.1 : Methodology of the research

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3.1 Experimental Procedure

The specimen model was created using the CAD programme CATIA and had dimensions of 80*35*4 mm which was converted to .STL file format and imported into the fast prototyping programme CURA. By employing FDM and taking into account the fabrication settings, specimens were built layer by layer with particular dimensions. Two distinct shades of black and translucent work pieces were used, together with 1.75 mm-diameter FDM filament. The welding of the specimens was accomplished utilising a fibre laser as a tool, a constant work holding pressure of 10 N, predetermined process parameters, and four passes.

Using a microprocessor-controlled 20-KN tensometer, the relative strengths of all the linked specimens were examined. Adjustments were made to the welded specimens to reduce the bending moments at the weld seam during the analysis; a spacer with the dimensions 35*30*4 mm was bonded on both sides of the specimen to create a correct alignment. Throughout the analysis, the crosshead speed was held constant at 1mm/min. The maximum load to failure per unit length of the weld was used to calculate weld strength.

3.2 Fabrication of Specimen

In the present work, plastic pieces have been welded. Two types of PLA thermoplastic materials used in this study as shown in figure 4.1 and specifications as given in Table 4.1.

Figure 3.1 A) Translucent PLA Filament B) Black PLA Filament

Table 3.1 PLA filament properties

Polymer properties	Description
Material	PLA 3D printing filament
Diameter	1.75 mm
Diameter tolerance	+/-0.03mm
Net weight	1KG/spool
Printing temperature	180-210 C

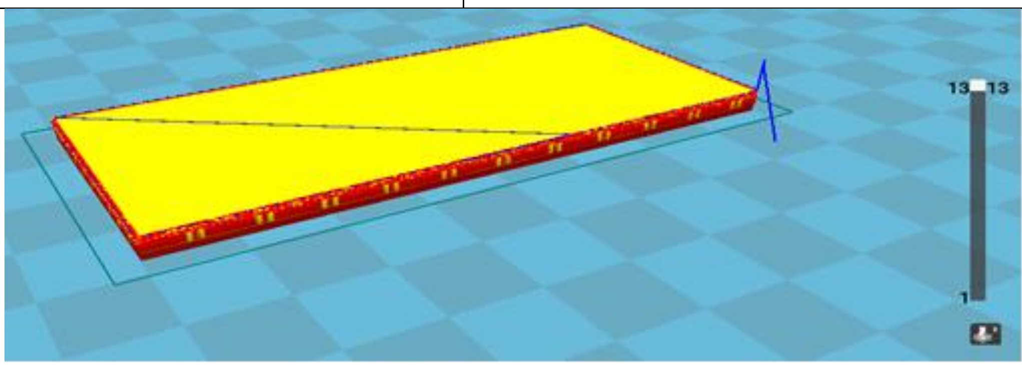

Figure 3.2 Interface of CURA - rapid prototyping software

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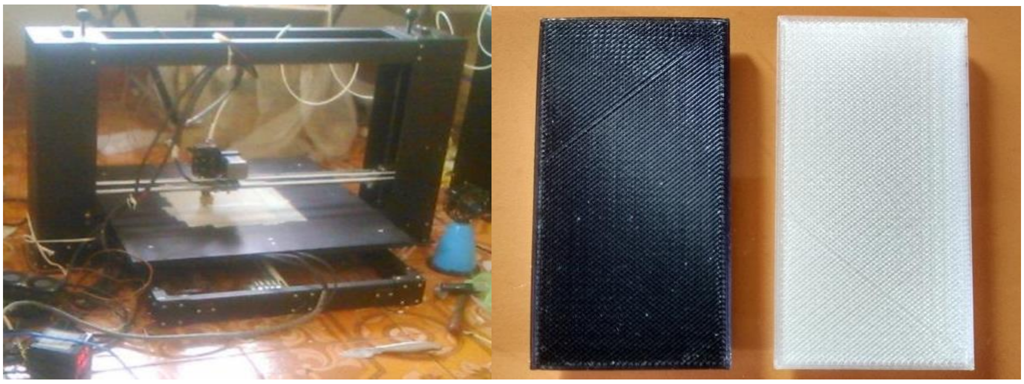

Figure 3.3 A) Specimen Building process in FDM B) Specimen after solidification

Table 3.2 Parameters to build specimens

Parameters	Values
Layer height in mm	0.1 mm
Shell thickness in mm	0.2 mm
Bottom/Top layer thickness in mm	0.5 mm
Fill density %	60%
Time taken to complete a specimen	22 minutes
Printing temperature C	210 C
Diameter of filament in mm	1.75 mm

3.3 Experimental Layout Design

Using Minitab 16 software, a design with 9 experiments was taken into consideration depending on the results of the initial analysis of the three components. Table 3.3 presents the factors and levels chosen for the design of experiments using Minitab 16 software. As seen in Figure 3.2, a L9 orthogonal array was used in the experimental design.

Table 3.3 Process parameters and Levels

Factor	Levels		
	Level 1	Level 2	Level 3
Power (W)	16	18	20
Welding speed (mm/s)	5	10	15
Standoff distance (mm)	210	230	250

Table 3.4 Experimental design for L9 array

Expt No.	Power (Watts)	Scanning speed (mm/s)	Stand-off distance (mm)
1	16	5	210
2	16	10	230
3	16	15	250
4	18	5	230

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5	18	10	250
6	18	15	210
7	20	5	250
8	20	10	210
9	20	15	230

3.4 Finite Element Analysis method

3.4.1 Methodology

The process of simulation is illustrated in the flow diagram of methodology as shown in fig 3.4.

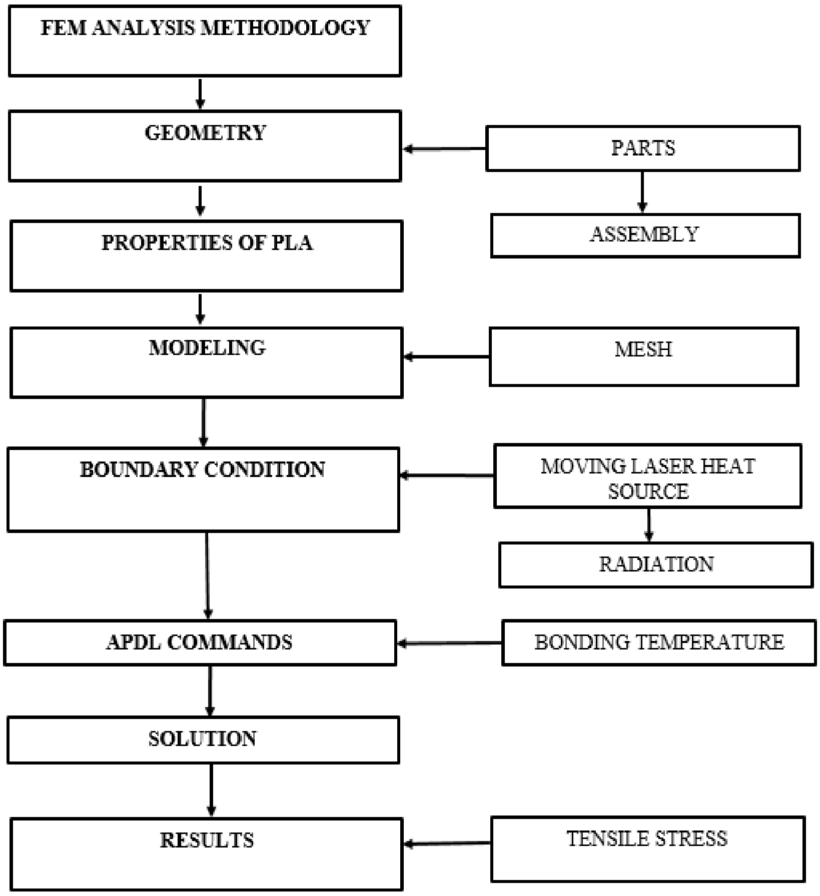

Figure 3.4 FEM Methodology

4.1 Experimental Results

4.1.1 Overview of Testing

Experimental plan, set up and procedure has been discussed in the previous chapter. Welding of lap joints, visual inspection, pull test and weld seam width measurement and SEM analysis was done. In this chapter results were considered and discussed. The photographic views of two welded samples after the pull test are shown in Figure 4.1 and Figure 4.2.

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Figure 4.1 (Left) Photographic view of the sample-1 after pull test showing fracture at the edge of the weld zone (Right) Photographic view of the sample (sample number 9) after pull test showing failure at weld zone

The results of pull test and measurement of weld width under metallurgical microscope shown in Table 4.1**.** An objective lens of 64X magnification was used for all the measurements of weld seam width. Three dimensions of weld seam width (W1, W2, and W3) were taken at different positions and then averaged.

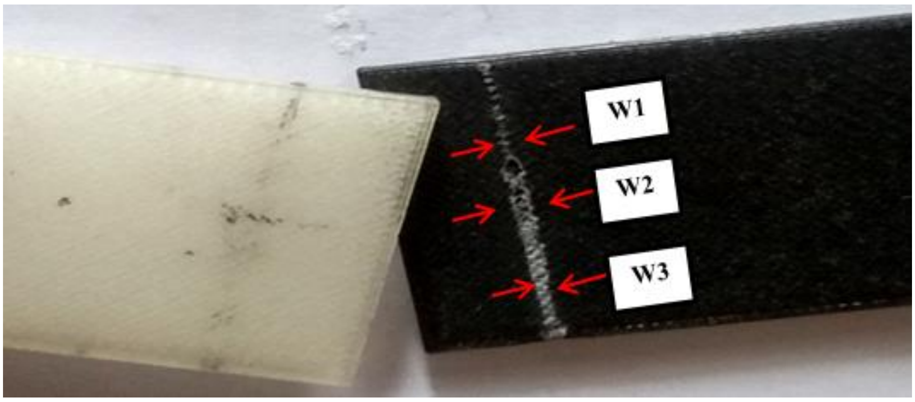

Figure 4.3 Measurement of weld width at three different locations of each sample

4.1.2 Taguchi Analysis

Taguchi method of design of experiment is a simple, effective and systematic approach to optimise parameters for performance and cost. It can optimise process parameters reducing fluctuation of system performance to source of variation.

Table 4.1 Experimental parameters and results

Expt No.	Power (Watts)	Scanning speed (mm/s)	Stand-off distance (mm)	Weld strength (N/mm^2)	Weld width (mm)
1	16	5	210	8.265	3.39
2	16	10	230	1.44	2.52
3	16	15	250	0.796	1.615
4	18	5	230	9.81	3.079
5	18	10	250	1.08	1.131
6	18	15	210	1.34	2.355
7	20	5	250	10.51	2.765
8	20	10	210	2.89	1.653
9	20	15	230	2.324	1.835

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4.2 Finite Element Analysis Results

Following diagrams show the development of tensile stresses in the fibre laser welded samples with respect to varying power and velocity as per the tabulated data from Table 4.3 .

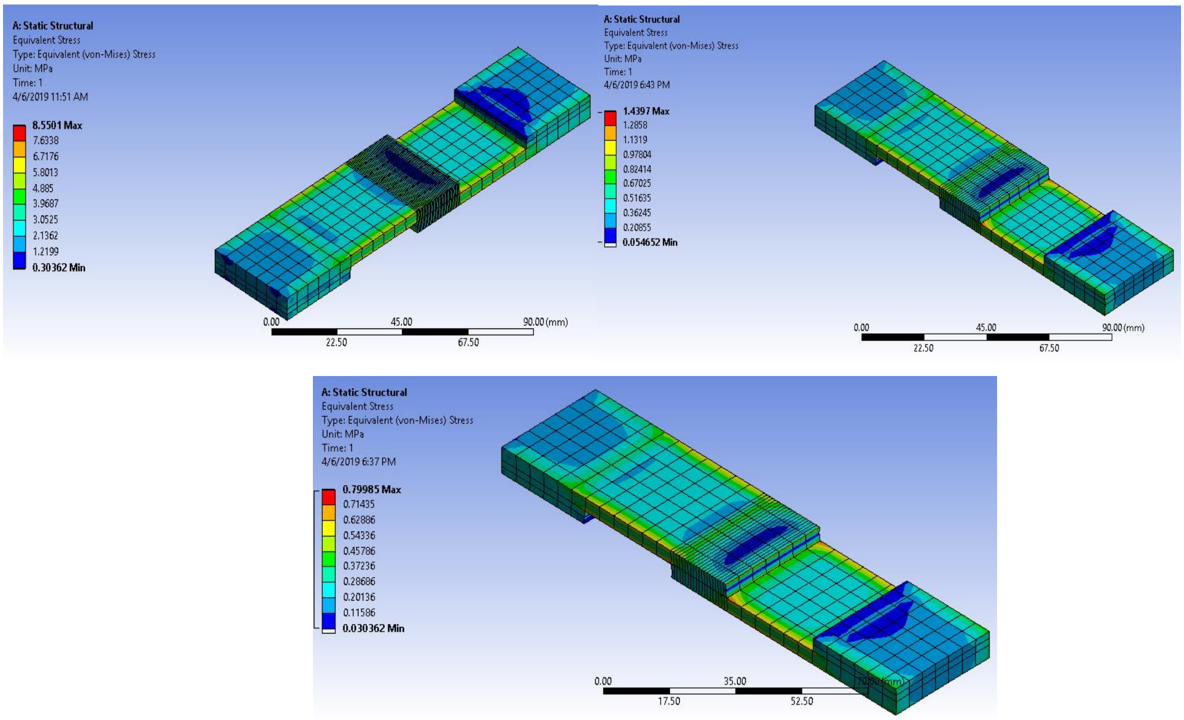

Figure 4.4 Tensile stress of trial 1, 2 and 3 (Power: 16, Velocity: 5, 10, 15 respectively)

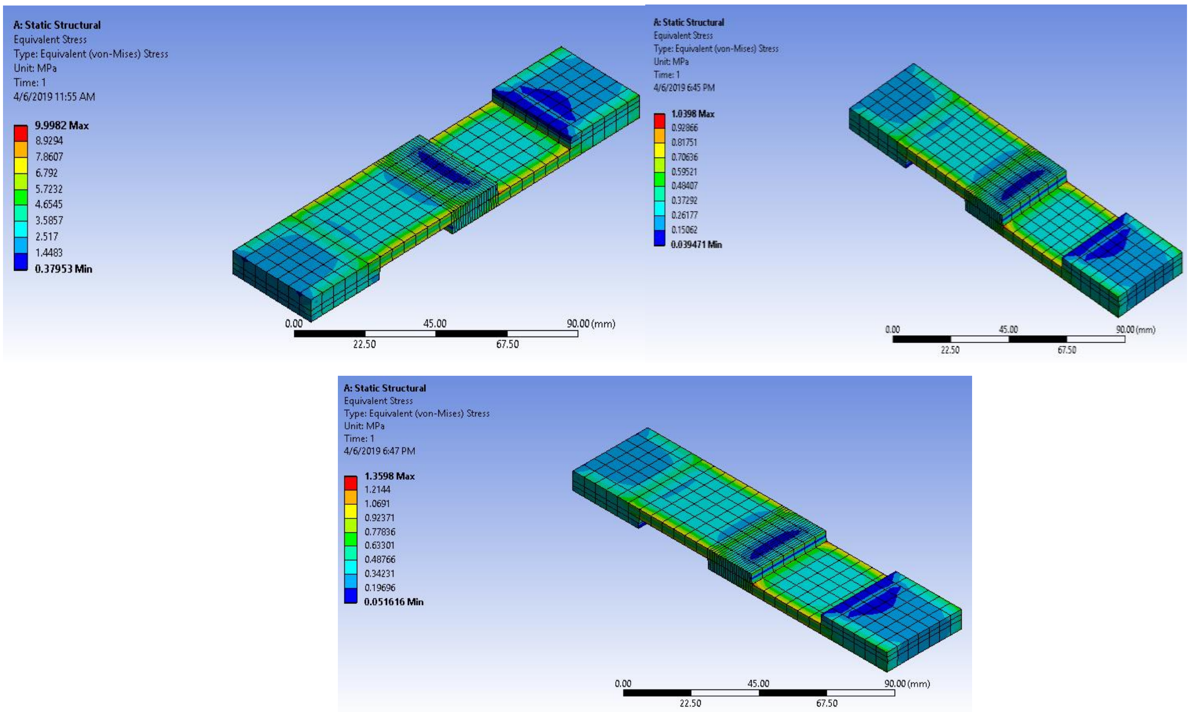

Figure 4.5 Tensile stress of trial 4, 5 and 6 (Power: 18, Velocity: 5, 10, 15 respectively)

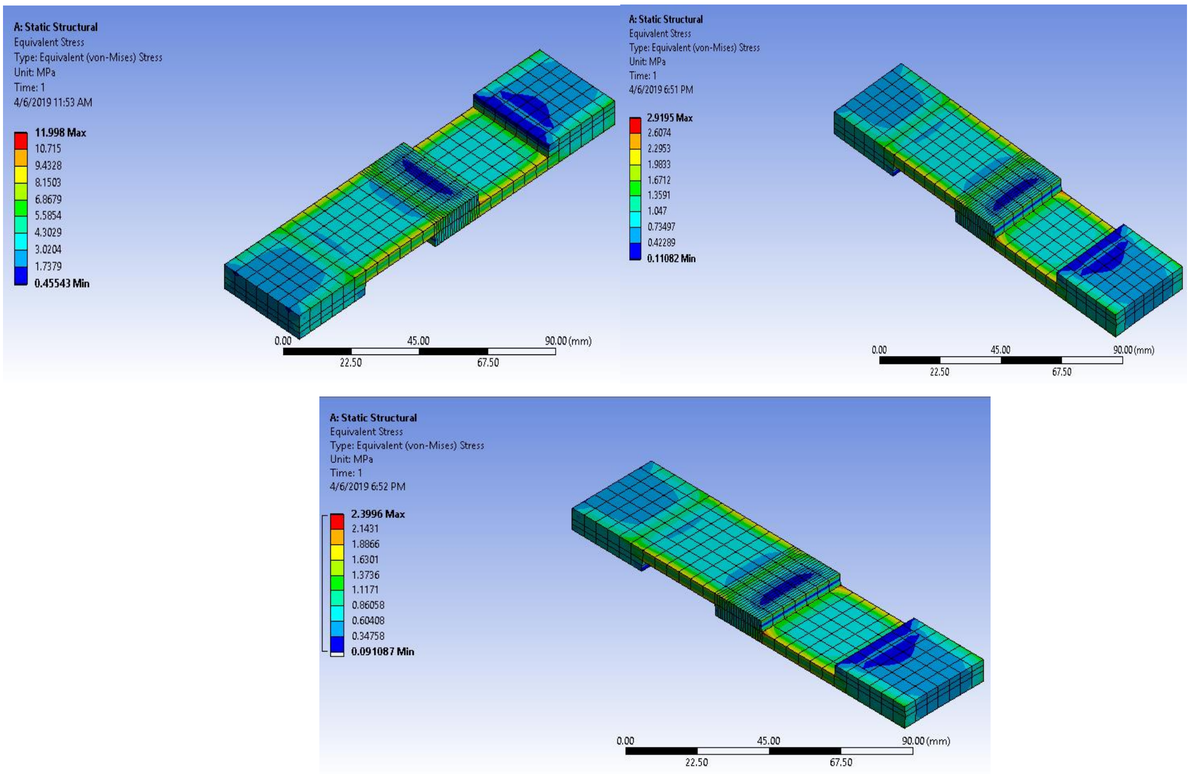

Figure 4.6 Tensile stress of trial 7, 8 and 9 (Power: 20, Velocity: 5, 10, 15 respectively)

Table 4.3 Results of FEM simulation

Sl no	Power(w)	Velocity (mm/s)	Tensile stress(Mpa)
1	16	5	8.550
2	16	10	1.439
3	16	15	0.799
4	18	5	9.998
5	18	10	1.039
6	18	15	1.359
7	20	5	11.99
8	20	10	2.919
9	20	15	2.399

Based on the simulation results the experiment No.7 is giving the best results as compared to experimental values at Power 20W and Velocity 5m/s.

5.3 Validation of FEA results with Experimental results

The final step in the experiment was to do validation of FEA results with the experimental results in order to find the error percentage between the theoretical laser welding process on PLA polymers and experimental laser welding process on PLA polymers. After finding the optimal level of the process parameters, the next step was to predict and authenticate the improvement of the parameters characteristics using the optimal level. The variation of the improvement of practical approach with respect to ideal approach can be found by this validation approach. By using an experimental approach, it was determined that the weld's strength was 10.51 N/mm^2 when compared to the ideal process parameters, such as power at 20W, scanning speed at 5 mm/s, and stand-off distance at 250mm. Weld strength was determined to be 11.998 N/mm^2 using the Finite Element Analysis method and ideal process parameters, such as power at 20W, scanning speed at 5 mm/s, and stand-off distance at 250mm. The comparison of the FEA and experimental data has been displayed in Table 4.4 shows the percentage of error of the experimental research relative to the ideal method..

Table 4.4 Comparison of results

Factors	Experimental Result	FEA Result	Percentage Error
Weld Strength (N/mm^2)	10.51	11.998	12.40%

6.1 Conclusion

In the current study, laser transmission welding was used to perform lap welding on two PLA plastic plates, each of which had a thickness of 4 millimetres. One of the plates was transparent, while the other was opaque. This was done under a variety of different welding settings. An L9 orthogonal array was built by taking into consideration laser power, scanning speed, and standoff distance, based on works that came before it. The tensile strength of the weld and the breadth of the weld seam were chosen to serve as the response parameters. The following findings have been reached based on the results of the experiments and the finite element analysis: the impacts of process factors such as power, scanning speed, and standoff distance on the width of weld seam and the joint strength have been discovered and analysed.

- It was determined via the process of single objective optimization that the optimal parametric condition for highest joint strength was P3 SS1 S2 (Power: 20W, Scanning speed: 5 mm/s and standoff distance: 230mm). P2 SS2 S3 was the optimal condition for achieving the smallest weld seam width, with the power being 18 W, the scanning speed being 10 mm/s, and the standoff distance being 250 mm. The Taguchi approach is used in order to do optimization with a single target.
- The Grey-Taguchi approach is used in order to do multi-objective optimization. P3 SS1 SOD3 was the optimal parametric condition for concurrently optimising the joint strength and the weld seam width. This was accomplished by maximising joint strength (Power: 20 W, Scanning speed: 5 mm/s and standoff distance: 250 mm).
- From Finite Element Analysis results, optimum parametric condition for maximisation of joint strength were P3 SS1 SOD3 (Power: 20W, Scanning speed: 5mm/s, Stand of distance: 250mm)
- The validation of FEA results with experimental results revealed the percentage of error as 12.40 %.

6.2 Scope for Future Work

The focus of the study was PLA laser transmission welding. The following region, however, may be expanded upon as future research:

- The information obtained through laser welding PLA can be employed in a variety of optimization strategies, and the results of each optimization strategy should be contrasted. The optimal optimization method should be used to achieve the desired outcome.
- By including "clamping pressure" or "laser wavelength" as one of the process factors, experiments and analyses can be carried out. Transparent-to-transparent plastic welding may be regarded as a significant and difficult topic of research.

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