Analysis of Laser beam welding of SS316L butt joints using Design of Experiments

Y. Krishnaiah\textsuperscript{1,2}, A.M.K. Prasad\textsuperscript{1}

\textsuperscript{1}Department of Mechanical Engineering, Osmania University, Hyderabad, India.
\textsuperscript{2}Department of Mechanical Engineering, Sreyas Institute of Engineering and Technology, Hyderabad, Telangana, India.

yaggadikrishna@gmail.com

Abstract. Process control plays a significant role in increasing customer demand for quality, performance, cost; safety and reliability are essential for continuous growth, securing a process that allows least distortion after the laser welding process by applying with Experimentation Design. In the current experiments, the parameters of Laser power, welding speed, and Argon shielding are being used with L4 orthogonal array. These variables were checked to find the best control level combination of output and its related least distortion and maximum tensile strength. The X-ray radiography has tested the welds' consistency and found that they are free from the surface and internal defects. The results show that welding speed, weld processes are critical parameter, and a shielding gas are not critical.

1. Introduction

The use of laser beam welding (LBW) is superior than using an arc welding technique since it is highly effective and consistent in terms of no additional spatter, and this has significant implications for the stability and structural integrity of the structure. Laser welding is accomplished with the assistance of a gas laser. Active medium, pumping system, and an optical resonator are required to operate laser equipment components properly. The emission-induced medium is located adjacent to the laser radiation systems, and it is here that the laser activity is essential. In order to investigate the effects of different Nd: YAG laser settings on thin magnesium alloy plates, Lung Kwang Pan \cite{1} employed Taguchi experiments. Tensile strength is optimized by controlling the shielding gas, the focal point, the pulse frequency, and the form of the beam. Among the CO\textsubscript{2} continuous laser welding technologies, Anawa \cite{2} is the most well-researched and best-practised. Dissimilar materials, such as AISI 316 stainless steel and AISI 1009 low carbon steel sheets, were joined together using a Taguchi technique to improve the minimum fusion zone scale. A welding and defocusing process that incorporates a variety of power parameters was used to achieve this improvement.

It was conducted with elastic-plasticity and temperature-dependent features to investigate distortion and stresses in a 1mm thick layer \cite{3-5}. Aavanish \cite{6} described various CO\textsubscript{2} and Nd: YAG laser techniques, as well as other experimental approaches for process optimization,
including Taguchi methods, in his paper on process optimization. Moratis et al [7] utilized a computer simulation to investigate residual stress and distortion production in aluminium laser-welding laps when conducting their research. It is discovered that the laser beam is located within the solidifying metal; its surface bounces via the dead-end capillary, which loses a significant amount of its energy through the two major modes of heat conduction and radiation. Buddu and colleagues [8, 15] utilized a CO2 laser beam welding technique on an 8mm thick plate with a 3.5kW laser power to fuse the plate to experiment. When comparing the weldments to the basis material, the results reveal that the mechanical characteristics of the weldments have improved.

Despite numerous researchers having researched these issues, there is still much attention on distortion and residual stresses in welded joints. Mackerle [9] and Dong [10] have proposed a comprehensive review of the pertinent subjects. Several destructive and non-destructive instrument for testing methods for residual stresses have been developed in recent years. Non-destructive ultrasonic methods are the most often utilized of these techniques. For many decades, a finite element (FE) model of the welding process (simulation) was employed to investigate the challenge of developing a comprehensive theory. Welding calculations are generally difficult to execute numerically owing to heat and mechanical factors. Using ANSYS, we can create an elastic-plastics, thermomechanical simulation that helps us state residual stresses and distortion in welds. Welding influences the phase transitions of products throughout the melting and solidification processes. This is important for determining the heat distribution through the weld joint so that the temperature condition may be estimated to aid in determining the material characteristics [11-13]. After analyzing the laser and TIG welding mechanism, the weldments' distortion and residual stress distribution was reported. Subashini et al [14] had carried out the experiments using CO2 laser with MIG (hybrid) welding process to analyze the weldability studies with a single-pass for 10mm thick plate of maraging steel. The studies show promising results in weld efficiency and microstructural properties. The laser power of 3.5kW was used for experimentation with a single pass.

In the present analysis, stainless steel 316L material was analyzed for welding properties, particularly for weld joint quality, distortion and tensile strength studies in nuclear fusion reactors. L4 experimental design was performed using the CO2 laser beam welding technique, and the weld distortion tested. And to analyse the of parameters, laser power, welding speed, and the argon flow rate.

2. Experimentation

In order to prepare for welding, it was necessary to stabilize the components and reduce the unpredictability of the noise. This was done after all of the fixtures and equipment had been established. Because the number of pieces in this experiment was kept to a clear minimum, there was no way to repeat it because it was only a necessary evaluation. Therefore, an S/N study of the signal to noise ratio was excluded from the report due to the above. An L4 orthogonal array of experimentation was chosen in order to examine the criticality of the specified parameters are identified. The control parameters that have been detected include Laser power, Welding speed, and Argon Flow Rate, all of which have two levels. Laser beam welding tests with 5mm thick plates of 110mm length and 80mm width are shown in Figure 1, which was performed with laser beam welding equipment. The experiment, the Laser beam machine was calibrated to produce a beam with a diameter of 2mm and a focused angle of 90°, respectively.

Here, the L4 orthogonal array is used for two separate test parameters in Table 1. They had analyzed and determined the important nature of the controls. The installation was not problematic and the price
was approximately correct. In order to account for a non-linear impact, two levels (Level-1 and Level-2) might be utilized for each parameter. Take the orthogonally viewed tests in table 3. Each variable has three parameters; the minimal need is two elements of one degree of freedom.

![Figure 1](image1.png)

**Figure 1** (a) CO2 Laser beam welding machine (b) laser beam weldments

**Table 1 Heat input of the weldment**

| Trial no. | Laser Power kW | Welding Speed m/min | Shield gas flowrate lit/min |
|-----------|----------------|----------------------|----------------------------|
| 1.        | 3.0            | 1.0                  | 10                         |
| 2.        | 3.0            | 1.5                  | 15                         |
| 3.        | 3.3            | 1.0                  | 15                         |
| 4.        | 3.3            | 1.5                  | 10                         |

All weldments obtained in all trials were free of surface cracks and defects, as shown by radiography examination. Figure 1 (b) has four pictures, which exhibits welded examples of similar welds of SS to SS (a-d). Aside from the visual inspection and hammer test, a radiograph will show a continuous white line with no flaws. The weldments is characterized for any macro flaws using an x-ray radiography method following the ASME SEC-VIII standard. Internal flaws like porosity, blowholes, and fractures will result in black dots on the radiograph. Figure 2 shows radiographs of SS to SS in Photos (a-d) with straight white lines, showing acceptable good homogenous welds.

In the welding process, distortion occurs during the non-uniform heating and non-cooling phases, both non-uniform. In the case of weldments, it is necessary to consider the distortion in both the transverse and longitudinal directions. In order to evaluate shape-based data, it was necessary to include thermal expansion, thermal conductivity, elasticity, and yield strength. Aside from physical characteristics, distortion is frequently influenced by welding processes, weld metal mass, welding procedures, welding duration, and weld speed, among other factors. The calculation of the angular distortion for the weldments is carried with Equation 1. The angular distortion of the weldment is expressed in degrees and the method of measuring are given figure 3.
\[ \theta = \sin^{-1}\left[ \frac{h_1 - h_2}{b} \right] \] \hspace{1cm} (1)

3. Result and Discussion

3.1. Weld quality

The aspect ratio of the weldment differed depending on the controlled parameters that were utilized. The internal quality of weldments is evaluated using an optical microscope and bead geometry of each joint at the lateral surfaces of the joints are given in figure 4. Weldments with greater penetration were preferred, and smaller beads widths were advised. As mentioned in 2, all-welded samples passed the radiograph test for weld quality. Additionally, the geometry and quality of the bead determine the solid solubility of the base material with the filler wire employed, which is reflected in the form and quality of the bead. These dimensions will be beneficial to individuals who conduct finite element analysis. As such, all samples were microstructured to determine the dimensions of the bead shape. A location identifier specifies the width of the root pass, filler pass, and cap pass, as well as the bead's overall height.
3.2. Distortion:

The distortion is measured on the top surface of the weldment cools to ambient temperature. The measurement is carried out using the vernier height gauge. The lower the better-quality characteristic is chosen for distortion measurement. Figure 5 shows the distribution of distortion measured values of the weldments. The trail-1 shows the better lower distortion. Distortion in trail-1 was 1.83° for heat input of 180 J/min. whereas for trail-2 is was 1.25° for heat input of 198 J/min, whereas in trail-3 and trail 4 is was 1.93° and 1.4°. The observed distortion in the weldments are varying with heat input (combinations of the process parameters) and the lowest distortion is seen in trail-2 and trail-4 of 1.25° and 1.4° where the welding is 1.5m/min with heat input of 120 J/min and 132 J/min.

Weld 2 and 4 specimens shows hiher tensile tested at room temperature. Weld 2 has a UTS of 575 MPa and weld 4 has a UTS of 594 MPa, whereas the yield stresses are 318 MPa and 280 MPa, respectively (Figure 6). All the Weld specimens failed at base metal.
4. Conclusions

To represent thick SS plates in nuclear reactors that require excellent weld butt joints, a research of the effect of LB joining of SS316L was undertaken. This research shows how laser joining of identical plates affects weldability, distortion, and tensile strength.

1. The technique of LBW uniform homogeneous welds was created using radiographic photographs and macrostructure pictures.
2. All of the weld beads were acquired in the correct size and form.
3. In all the welds, distortions were within the acceptable limits of 2° degrees.
4. The fusion zone showed normal epitaxial growth with defect free porosity and an exceedingly small heat-affected zone.
5. Tensile strength was equivalent to that of the parent metal, showing good laser weldability.

References
[1] Pan LK, Wang CC, Hsiao YC, Ho KC.2005. Optimization of Nd:YAG laser welding onto magnesium alloy via Taguchi analysis. Optics & Laser Technology, 37(1), pp.33–42.
[2] Anawa, E.M. and Olabi, A.G., 2008. Using Taguchi method to optimize welding pool of dissimilar laser-welded components. Optics & Laser Technology, 40(2), pp.379–388.
[3] Deng, D., 2009. FEM prediction of welding residual stress and distortion in carbon steel considering phase transformation effects. Materials & Design, 30(2), pp.359–366.
[4] Deng, D. and Murakawa, H., 2008. FEM prediction of buckling distortion induced by welding in thin plate panel structures. Computational Materials Science, 43(4), pp.591–607.
[5] Deng, D., Murakawa, H. and Shibahara, M., 2010. Investigations on welding distortion in an asymmetrical curved block employing numerical simulation technology and experimental method. Computational Materials Science, 48(1), pp.187–194.
[6] A. K. Dubey and V. Yadava.: Experimental study of Nd:YAG laser beam machining-An overview, Journal of Materials Processing Technology, vol.195, No.1–3, pp. 15–26, 2008.
[7] Moraitis, G.A. and Labeas, G.N., 2008. Residual stress and distortion calculation of laser beam welding for aluminum lap joints. Journal of Materials Processing Technology, 198(1-3), pp.260–269.
Buddu RK, Chauhan N, Raole PM, Natu H. Studies on mechanical properties, microstructure and fracture morphology details of laser beam welded thick SS304L plates for fusion reactor applications. Fusion Engineering and Design; 2015,95:34–43.

Mackerle J. Finite element analysis and simulation of welding: a bibliography (1976-1996). Medel Simul Mater Scie. 1996;4(5): 501-533.

Dong P. Residual stresses and distortions in welded structures: a perspective for engineering applications. Science and Technology of Welding and Joining. 2005;10(4):389-398.

H. Vemanaboina, S. Akella, A. Uma Maheshwer Rao, E. Gundabattini, and R. K. Buddu, “Analysis of thermal stresses and its effect in the multipass welding process of SS316L,” Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering, p. 095440892096506, 2020.

H. Vemanaboina, G. Edison, S. Akella.: Distortion control in multipass dissimilar GTAW process using Taguchi ANOVA analysis, International Journal of Engineering and Technology, vol. 7, No.3, p. 1140-1144, 2018.

Vemanaboina H, Akella S, Kumar B. Distortion control in Laser beam welding using Taguchi ANOVA analysis. FME Transactions; 2020;48(2):180–6.

Subashini, L., Prabhakar, K. V. P., Gundakaram, R.C., Ghosh, S., and Padmanabham, G.: Single Pass Laser-Arc Hybrid Welding of Maraging Steel Thick Sections, Materials and Manufacturing Processes, vol. 31, No. 16, pp. 2186–2198, 2016.

H. Vemanaboina, E. Gundabattini, S. Akella, A. C. U. M. Rao, R. K. Buddu, P. Ferro, and F. Berto, “Mechanical and Metallurgical Properties of CO2 Laser Beam INCONEL 625 Welded Joints,” Applied Sciences, vol. 11, no. 15, p. 7002, 2021.