MECHANICAL AND METALLURGICAL CHARACTERISATION OF CO₂ LASER BEAM WELDING AISI 4130 AND AISI 310 SHEETS OF STEEL

BIJIVEMULA Narayana Reddy^{1*}, POTHUR Hema², CHEVIREDDY Eswara Reddy³

^{1*}*Department of Mechanical Engineering, Chadalawada Ramanamma Engineering College,
Tirupati, India, e – mail: nari.biju@gmail.com*

^{2,3}*Department of Mechanical Engineering, S. V. University, Tirupati-517502, India,
e – mail: hemasvumech@gmail.com, ce_reddy@yahoo.com*

Abstract: Laser Beam Welding (LBW) is the fusion welding technique in which coalescence is produced by heating the work piece by impingement of concentrated beam of laser light. In this paper a full depth butt welding of alloy steel AISI 4130 and stainless steel AISI 310 of 2 mm thickness by using CO₂ Laser Beam Welding machine has been performed. Design of experiment is done by using Taguchi method L₂₅ i.e. level 5 by considering process parameters i.e. power, welding speed, beam angle, focal point position and focal length. The experimental output results that are measured for the mechanical properties of welds (Ultimate Tensile Strength and Hardness). The analysis was carried out to explain the influence of the LBW processing parameters values on the mechanical and microstructural aspects. The weld Joint is analysed by Optical Microstructure and Scanning Electron Microscopy (SEM). The Energy Dispersive X-Ray Analysis (EDAX) was carried out to determinate the chemical composition of the weld zone.

KEYWORDS: Laser Beam Welding, Ultimate Tensile Strength, Micro Hardness, HAZ, SEM, EDAX.

1 Introduction

A variety of metals are being used for large scale manufacturing / production of products in the industrial sector to meet the global market demand with the possibility of improving the quality at lower costs. Such phenomenon has resulted in the investigation of modern technologies to weld dissimilar metals for large scale industrial applications. Among the present, Laser Beam Welding of metallic plates offers considerable advantages over the conventional techniques. Some of these advantages include precision of operation, local processing, fast processing time, and low cost [1]. The proper selection of welding parameters is necessary for defect-free welded joints. In addition, high temperature gradients developed in the welded section result in high stress fields in this region, which can limit the practical applications of the welded products. The model study gives physical insight into the welding process, which provides useful information on the process control and stress levels in the welding sections [2].

With the progress of new made material, the need for welding of complex shape with various applications is on strong demand in the industry [3]. Laser Beam Welding is used extensively due to its small and narrow welding zone [4]. Due to narrow focusing zone of the laser beam, a very low heat input is produced in the weld bead which in turn creates no HAZ or a very narrow HAZ. Moreover, the less residual stress is produced in the weld metal and the less deformation is produced in the weld bead [5].

During laser beam welding of dissimilar materials (having different metallurgical and mechanical properties), the selection of proper welding variables is very important, in order to

limit the extension of the Heat Affected Zones, to avoid the alteration of the mechanical and microstructural properties of the joint.

Alloy 310 is an austenitic stainless steel developed for use in high temperature corrosion resistant applications. The alloy resists oxidation under mildly cyclic conditions. Because of its high chromium and moderate nickel content, Alloy 310 is resistant to sulfidation and can also be used in moderately carburizing atmospheres. AISI 4130 alloy steel contains chromium and molybdenum as strengthening agents. It has low carbon content, and hence it can be welded easily. The datasheet given below provides more details about AISI 4130 alloy steel. In the welding process the chemical elements diffusion influences the microstructure, cracking tendency and quality of the joint.

2 Literature Survey

Weld quality mainly depends on the weld joint mechanical-metallurgical characteristics of the welded joint which has a direct relationship with the type of welding process being used and its input process parameters, Subhas Chandra et al., [6]. Pavol et al., [7] have modelled and analysed the temperature distribution in the welding of metals by using laser welding process in FEM, the temperature of the metal varies greatly from the ambient temperature to the evaporation temperature of the metal at the point of heating in a very short time. The temperature distribution based on the weld zones are analysed. Prasad et al., [8] have investigated on analyze the breaking load of single lap joint using hybrid joining techniques for alloy steel AISI 4140 and mild steel as base material by experimental and optimized by Taguchi method and neural network.

Investigations on the microstructure and mechanical properties of AISI 4130 stainless steel and AISI 304 low alloy steel joints obtained by Gas Tungsten Arc Welding, Electron Beam Welding and Friction Welding are conducted, Arivazhagan, et al., [9]. Therefore, for better quality and bead formation, Electron Beam Welding is to be studied. Later, A review on Laser Beam Welding research shows that Ti-Al alloys combination gives better metallurgical and mechanical properties than other combination consisting of stainless steel-Al, Cu-Al and Ti-Al and thus focusing on Al to other materials presented, Kalaiselvan, et al., [3]. Further, the microstructures and the formation mechanism of a stainless steel/copper dissimilar joints by laser welding are examined, Shuhai Chen, et al., [4]. Therefore, the quantity of fused copper has to be restricted during the laser welding of stainless steel and copper. The metallurgical and mechanical properties of dissimilar laser welding of 304 and MS materials have been studied, Saumil Bhatt and Dhaval Soni, [10]. GTAW method was used for obtaining of dissimilar joints of AISI 4130 and AISI 316 steels, Mostaan, et al., [11] and Scanning Electron Microscope (SEM) and Energy Dispersive Spectroscopy (EDS) was used for analyse the welding interface. The literature shows that the main problems arising during welding are the deviation of the laser beam angle and to maintain focal position or of focal length on steel surface during LBW. Further, metallographical and SEM with EDAX are gaining importance in butt joint analysis.

In this study, two dissimilar steel has been welded. One sample is a 4130 steel and the other is 310 stainless steel trade mark. The tensile strength and hardness were measured on the welded joint. The morphological changes in microstructure of the welded zone were examined using optical microscopy and Energy Dispersive X-Ray Analysis (EDAX).

3 Experimental Process

The experiments start with the selection metals for welding and is explained in the following sections.

3.1 Metals Selections

First step starts with selection of metals for experimentation. AISI 4130 alloy steel and AISI 304 stainless steel plates are taken for the investigation. The dimensions of the plates consist of 140 mm length, 100 mm width and 2 mm thickness. The chemical composition of the metals is shown in Table 1. Then the specimen (work pieces) for LBW are prepared to required dimensions using Wire cut EDM (Fig. 1), in order to obtain smooth edges to achieve close and qualitative joints.

Table 1 Chemical Composition base metals

Element Wt. (%)	AISI 4130	AISI 310
C	0.28	0.019
Mn	0.47	1.81
Si	0.21	0.54
P	0.016	0.033
S	<0.005	<0.005
Cr	0.84	17.94
Mo	0.16	0.31
Ni	-	10.53

Fig. 1 Specimen wire cut EDM

3.2 Experimental Work

Experiments relating to the joining of two dissimilar metals AISI 4130 and AISI 310 Steels by CO₂ LBW machine are carried out on Trumpf Lasercell- TLC1005. Specifications of the machine are shown in Table 2 followed by actual experimental setup in Fig. 2.

Table 2 CO₂ LBW machine specifications.

Name	Specification
Power range (W)	200-4000
Wave length (μm)	10.6
Flow pressure (bar)	15
Beam dia (mm)	2
Frequency (Hz)	20000
Shielding gas	Argon (Ar)
Shielding gas with a flow rate (l/min)	20

Fig. 2 Experimental Setup

3.3 Process parameters and their levels

As a first step of experimental work, independent variables and their levels are chosen based on L₂₅ as shown in Table 3. Then, at second stage, experiments are conducted with trial weld runs by changing input parameters each at a time, so as to attain full penetration, with smooth root bead without any welding defects. In the table indications P-Laser Power, S-Welding Speed, θ-Beam Angle, F-Focal Point Position and L-Focal Length.

Table 3: Independent variables and experimental design levels

Levels	P (Watts)	S (m/min)	θ (degrees)	F (mm)	L (mm)
Level-1	1400	1.2	88	-0.2	16
Level-2	1600	1.4	89	-0.1	17
Level-3	1800	1.5	90	0	18
Level-4	2000	1.8	91	0.1	19
Level-5	2200	2.0	92	0.2	20

3.4 Experiments with LBW

Specimen plates of two dissimilar metals, AISI 4130 and AISI 310 Steel sheets are abutted together for joining by CO₂ Laser Beam. The plate edges are prepared after cleaning with acetone and then ensured that the contact gap is maintained along weld line of LBW. The specimen plates are clamped rigidly to avoid any deformation caused by thermal loading. Based on the experimental design levels of process parameters (Table 3). The parameters are selected at each level. The Laser beam is generated by directing the beam perpendicular to the mating of plates in order to obtain the perfect weld bead. The welding operation is accomplished as per the design matrix in systematic order according to the selected parameters. Each joint of two dissimilar metals is obtained by CO₂ Laser Beam. Experiments are repeated till 25 joints are obtained. Few samples of the joints obtained by LBW are shown in Fig. 3.

Fig. 3 Samples of joints produced by CO₂ LBW experiments

Specimens of 55×10×3 mm are cut from the welded joints on CNC wire cut EDM as per standards of ASTM E 8M-01. Tensile tests are conducted on FIE Universal Tensile machine UTES 40. The samples after testing are shown in Fig. 4. The samples for Vickers Micro Hardness are encapsulated in plastic mould using hot mounting press. The samples are tested for hardness on Wolpert Micro Vickers Tester 402-MVD by applying a load of 1000g for 10 seconds duration shown in Fig. 5. Results of UTM and MH for each sample are presented in Table 4

Fig. 4 (a) FIE Universal Tensile Testing

Fig. 4 (b) Samples after Tensile Tested

Fig. 5 (a) Micro Vickers Hardness Tester 402-MVD Fig. 5 (b) Samples for Micro Hardness

Table 4 Taguchi DOE and Experimental Results.

S. No.	Process Parameters					Output Results	
	P (W)	S (m/min)	θ (degrees)	F (mm)	L (mm)	UTS (MPa)	MH (HV1)
1.	1400	1.2	88	-0.2	16	498.46	536
2	1400	1.4	89	-0.1	17	554.61	536
3.	1400	1.6	90	0	18	555.38	520
4..	1400	1.8	91	0.1	19	611.54	300
5.	1400	2	92	0.2	20	295.38	228
6.	1600	1.2	89	0	19	608.46	420
7.	1600	1.4	90	0.1	20	170.77	228
8.	1600	1.6	91	0.2	16	470.77	450
9.	1600	1.8	92	-0.2	17	574.61	184
10.	1600	2	88	-0.1	18	400.00	320
11.	1800	1.2	90	0.2	17	610.00	463
12.	1800	1.4	91	-0.2	18	604.61	370
13.	1800	1.6	92	-0.1	19	620.00	200
14.	1800	1.8	88	0	20	597.69	340
15.	1800	2	89	0.1	16	363.08	300
16.	2000	1.2	91	-0.1	20	609.23	450
17.	2000	1.4	92	0	16	610.00	195
18.	2000	1.6	88	0.1	17	577.69	250
19.	2000	1.8	89	0.2	18	607.69	400
20.	2000	2	90	-0.2	19	582.31	205
21.	2200	1.2	92	0.1	18	568.46	560
22.	2200	1.4	88	0.2	19	582.31	570
23.	2200	1.6	89	-0.2	20	620	195
24.	2200	1.8	90	-0.1	16	616.15	202
25.	2200	2	91	0	17	610.77	250

4 Effect of Process Parameters on Output Responses

The performance curves are drawn based on the output responses for various strengths as discussed below.

4.1 Laser Power

Performance curves are drawn in Fig. 6 to show the effect of laser power on UTS and hardness values.

From the graph plotted in Fig. 6, it can be seen that as the laser power increase from 1400 W to 2200 W, the output characteristics are varying. At laser power of 2000 W and welding speed of 1.6 m/min, the output characteristics UTS and hardness have attained the maximum values. Hence, can be said that the best couple for the laser power and speed values is reached for these values.

Fig. 6 Performance characteristic curves for power

Fig. 7 Performance characteristic curves for Speed

4.2 Welding Speed

The effect of welding speed on UTS and Hardness is shown in Fig. 7. For the welding speed values higher than 1.6 m/min, the hardness start to decrease dramatically. Hence, the optimal characteristics values, both for UTS and hardness, are obtained for a welding speed of 1.6 mm/ min.

4.3 Beam Angle

From the graphs, Fig. 8, it can be found that as the beam angle increases from 88° to 92° , the output characteristics UTS and Hardness are varying. But when speed increases the UTS and Hardness of weld joint is also increasing. The output characteristics, UTS have attained maximum upto the beam angle of 91° and then the UTS falls. Hence, the best results are obtained for a beam angle value of 91° .

Fig. 8 Performance characteristic curves for Beam Angle.

Fig. 9 Performance characteristic curves for focal point position.

4.4 Focal Point Position

From the graph, Fig. 9, it can be observed that the focal point position has a significant effect on UTS and Hardness. In addition, it can be observed the slight decrease of UTS and hardness when the focal point position ranges from -0.2 mm to 0.2 mm, beginning with the 0 mm focal point position value. From Fig. 9, it is also evident that the UTS and Hardness are maximum at the focal point position of -0.2. When the beam is focussed towards the right side, a decrease trend is observed in all the two characteristics decrease.

4.5 Focal Length

Performance curves are drawn for the effect of Focal length on UTS and Hardness and as shown in Fig. 10.

Fig. 10 Performance characteristic curves for focal Length

From the graph, Fig. 10, it can be observed that as the focal length ranges from 16 mm to 20 mm, the output characteristics, UTS slightly decrease with an increase in focal length 16 mm to 20 mm. But when focal length increases from 16 mm to 17 mm, the hardness values decrease. Subsequently, only the hardness increase with the laser light intensity. Thus, it is evident that the UTS and Hardness are optimum when the focal length is of 16 mm followed by value of 18. mm.

5 Results and Discussion

In this section have been analyzed the effects of the parameters values of the laser welding regimes on the microstructural aspects of the welded joint.

5.1 Optical Microstructure of AISI 4130 Base Material

The microstructure analysis of the as received base material AISI 4130 steel, is shown in Fig. 11.

The AISI 4130 stainless steel has equiaxed grains of austenite with infrequent twinning. The microstructure consisting of fine grains Ferrite and which are shown in Fig. 11. The chemical composition of the AISI 310 stainless steel contains Fe, Cr, Mn, C, Si, P, Mo, S (Table 1).

5.2 Optical Microstructure of AISI 310 Base Metal

The microstructure analysis of the as received base material AISI 310 steel is shown in Fig. 12. The microstructure consisting of Annealing Twins in an Austenitic matrix and which are shown in Fig. 12. The chemical composition of the AISI 310 stainless steel contains Fe, Cr, Ni, Mn, Si, P, Mo, C, S (Table 1).

Fig. 11 Optical Microstructure of AISI 4130 steel base metal

Fig. 12 Optical Microstructure of AISI 310 steel base meta

5.3 The microstructure of Heat Affected Zones

The interface on the weld zone on the AISI 310 side and AISI 4130 side are shown in Fig. 13 (a) & (b). From the optical micrograph analysis it is clear that grain growth occurred from base metal to weld metal and the change in the microstructure of weld zone was analysed. A distribution of the elements along the weld line that cross the Heat Affected Zone between the two dissimilar metals as shown in Fig. 13.

(a). HAZ of 310

(b). HAZ of 4130

Fig. 13 Optical Microstructure of HAZs

Microstructure at the interfaces of AISI 310 side is shown in Fig 13 (a). HAZ of AISI 310 shows complete fusion between weld and AISI 310 base metal. The interface on the weld zone on AISI 310 metal microstructures shows delta Ferrite stringers and carbide precipitation in an Austenitic matrix. Similarly, Interfaces of AISI 4130 side is shown in Fig 13 (b). HAZ of AISI 4130 shows complete fusion between weld and AISI 4130 base metal.

5.4 Optical Microstructure and SEM analysis with EDAX of Fusion Zone

Weld metal microstructure solidification changed from cellular Fine Ferrite Grains and Annealing Twins in an Austenitic steel because of heat input which resulted from the higher cooling rate and therefore a finer microstructure. In the weld metal region Austenitic-Ferritic (AF) / Ferritic-Austenitic (FA) modes of solidification occurred and it is clearly seen in Fig.14 (a).

Weld integrity is so well that weld line is completely disappeared in the both side of weld zone. No weld defects or inclusions are observed at weld interface. The weld zone in LBW joint is very small and at the adjacent interface surface (HAZ) as shown in the Fig. 14 (a). The weld zone consists of Pearlite, Ferrite and Martensite were also shown.

The SEM and EDAX analyses of the fusion zone of the experiment are shown in Fig. 14 (b) & (c). The EDAX analysis of the weld zone illustrated that it possessed major elements like Fe, C, Cr, Mn, Ni, Mo, Si and P. The percentage composition of these elements are shown in the Fig. 14 (d). From the above figures, it is evident that the elements like Cr, Ni, Mo, Mn diffused from the base metal to form secondary precipitates in the weld zone. thereby, increasing the strength of the joints due to the presence of potassium in the secondary precipitates.

Fig. 14 Weld Zone Microstructure (a) Optical Microstructure, (b) SEM analysis, (c) EDAX analysis and (d) EDAX Elements

CONCLUSIONS

Conclusions based on the experimental results are shown in the following:

- Sound welds are obtained on joining of dissimilar AISI 4130 and AISI 310 steels by LBW.
- LBW is suitable for welding AISI 4130 with AISI 310 steels for industrial applications owing to high welding speed and highest UTS 620 MPa and hardness 570 HV1 as obtained for the experimental joints.
- The AISI 4130 and AISI 310 weld joint UTS and hardness are increasing with Laser Power 1400W to 2200W. A trend of increase in UTS and Hardness was observed with increase in Laser Power and Speed.
- Complete fusion between weld and base metal. The microstructure in the weld joint was gradually transited to interdendritic structure in the interface. The fusion zone containing a mixture of fully Pearlite, Ferrite and Martensite structures.
- In the weld zone had both low density elements (Si, N, and C) and high density elements (Cr, Ni and Fe). Fe addition in the weld metal decreased the solubility of Nb in austenite.

ACKNOWLEDGEMENTS

The authors are highly grateful to M/S. Scolarien Bicycles Pvt. Ltd. for their help in carrying out the sample preparation of weld joints. They also acknowledge the assistance and support provided in the manufacturing Laboratory of Department of Mechanical Engineering, SVU College of Engineering, Tirupati for supporting them in machining of weld plates and also thankful to M/S. Magod Laser Pvt Ltd, Peenya, Bengaluru for providing experimental setup/Laser beam Welding Machine to conduct the experiment smoothly.

REFERENCES

- [1] Narayana Reddy, B., Hema, P., Eswara Reddy, C. and Padmanabhan, G. "Role of Laser Beam in Welding and Assembly: A Status Review" Proceeding of 10th COPEN, Dept. of Mechanical Engineering, IIT Madras, pp. 1056 – 1060, **2017**. <https://www.copen.ac.in/proceedings/copen10/copen/246.pdf>
- [2] Narayana Reddy, B., Hema, P., Vishnu Vardhan, G. and Padmanabhan, G. "Experimental Study of Laser Beam Welding Process Parameters on AISI 4130-309 Joint Strength", Materials Today: Proceedings, Elsevier 22 (4), pp. 2741 – 2750, **2020**. DOI: 10.1016/j.matpr.2020.03.405
- [3] Kalaiselvan, K., Elango, A. and Nagarajan, N. M. "Comparative Studies on Dissimilar Metals Thin Sheets using Laser Beam Welding-A review", International journal of Mechanical, Aerospace, Industrial, Mechatronics and Manufacturing Engineering 8 (10), pp. 1753 – 1756, **2014**. DOI: 10.5281/zenodo.1097469
- [4] Shuhai Chen, Jihua Huang, Jun Xia, Hua Zhang, Xingke Zhao "Microstructural Characteristics of a Stainless Steel/Copper Dissimilar Joint Made by Laser Welding", Metallurgical and Materials Transactions A 44 (8), pp. 3690 – 3696, **2013**. DOI: 10.1007/s11661-013-1693-z
- [5] Stanciu, E. M., Pascu, A., Tiorean, M. H., Roata, I. C., Voiculescu, I., Hulka, I., Croitoru, C., "Dissimilar Laser Welding of AISI 321 and AISI 1010", Technical Gazette 25 (2), pp. 344 – 349, **2018**. DOI:10.17559/TV-20160722151049
- [6] Moi, S. Ch., Pal, P. K., Bandyopadhy, A., Rudrapati, R. "Determination of tungsten inert gas welding input parameters to attain maximum tensile strength of 316l austenitic stainless steel", Strojnícky časopis – Journal of Mechanical Engineering 68 (3), pp. 231 – 248, **2018**. DOI:10.2478/scjme-2018-0037
- [7] Sejš, P., Világoš, T. "Fem simulation of thermal cycles during laser welding of aluminium", Strojnícky časopis – Journal of Mechanical Engineering 68 (1), pp. 89 – 94, **2018**. DOI:10.2478/scjme-2018-0009
- [8] Lalta, P., Rahul, K. "Study on Breaking Load of Single Lap Joint Using Hybrid Joining Techniques for Alloy Steel AISI 4140 and Mild Steel: Taguchi and Neural Network Approach", Strojnícky časopis – Journal of Mechanical Engineering 68 (1), pp. 51 – 60, **2018**. DOI: 10.2478/scjme-2018-0005
- [9] Arivazhagan, N., Surendra, S., Satya, P, Reddy, G. M. "Investigation on AISI 304 austenitic stainless steel to AISI 4140 low alloy steel dissimilar joints by Gas tungsten arc, Electron beam and Friction welding", Materials and Design 32, pp. 3036 – 3050, **2011**. DOI: 10.1016/j.matdes.2011.01.037
- [10] Saumil Bhatt, R. Dhaval Soni, K. "Experimental and Metallurgical investigation on laser welding of dissimilar materials", International Research Journal of Engineering

and Technology 05 (5), pp. 205 – 213, **2018**. <https://www.irjet.net/archives/V5/i5/IRJET-V5I540.pdf>

- [11] Mostaan, H., Poorkabirian, M., Rafiei, M. “The Interface Structure in Dissimilar Welding of AISI 4130 to AISI 316L Steels Using ERNiCr-3 Filler Metal”, International Journal of ISSI 15 (1), pp. 1 – 8, **2018**. http://journal.issiran.com/article_32013.html.