Dissimilar Laser Welding of NiTi Alloy with Ferrous and Non-ferrous Material: Optimization of Process Parameters

Soumya Ranjan Parimanik[1], *Trupti Ranjan* Mahapatra[1*], *Debadutta* Mishra[1] and *Akshaya Kumar* Rout[2]

[1] Department of Production Engineering, Veer Surendra University of Technology, Burla, Odisha, 768018, India
[2] School of Mechanical Engineering, KIIT Deemed to be University, Odisha, 751024, India

Abstract. NiTi Shape Memory Alloy (SMA) is extensively utilized in various high-performance engineering industries such as medical devices, aerospace, air-craft structures, micro-electrical and electronic components, and more, owing to its exceptional properties, including shape memory effect (SME), superelasticity, and biocompatibility. Nonetheless, due to its distinct characteristics, achieving a suitable joint of NiTi alloys is a challenging task. Therefore, scientists have been dedicating significant efforts to the joining of this alloy. This current research explores the weldability of NiTi wires with stainless steel wire and copper wire using Laser. The micro-hardness and the tensile strength of the weld joint are acquired according to Taguchi design of experiment so as to identify the significance of the control factors (laser power, scan speed and focal length). Moreover, simultaneous optimization of multi performance characteristics is also attempted using Utility concept. The results from the confirmation runs showed that the predicted optimal machining parameters has im-proved the individual as well as the multiple performance characteristic.

1 Introduction

Shape memory alloys (SMAs) such as NiTi or Nitinol have the remarkable ability to revert from a deformed shape to their original shape upon the application of external heat or mechanical load [1]. These alloys have become highly sought-after due to their outstanding properties, including excellent corrosion resistance, bio-compatibility, non-magnetic nature, as well as impressive mechanical and thermo-mechanical properties. As a result, Nitinol has found numerous applications across a wide range of fields, such as automobile, aerospace, biomedical, robotics, MEMS, sensors and actuators, hydro-space, structural and civil applications [2].

In the review Oliveira et al. [3], various techniques for welding and joining Nitinol SMAs are examined for both similar and dissimilar combinations. The most prevalent method found for joining Nitinol is laser welding, which is effective in joining Nitinol with other materials

* Corresponding author: trmahapatra_pe@vssut.ac.in

such as Steel or Ti6Al4V, even when the mate-rials were dissimilar. Mehrpouya et al. [4] reviewed the laser welding technique of NiTi. Both similar and dissimilar combinations of laser welding of NiTi wires, sheets, plates and rods were discussed. It was also inferred that effect of shielding gases influences the penetration ratio. The research conducted by Zeng et al. [5] focused on dissimilar laser welding of Ni wire and Cu sheet and examined the functional fatigue behaviour. Their findings indicated that the microstructure of the welded joint was altered by laser welding, and the presence of copper strengthened the weld. Meanwhile, Ng et al. [6] investigated the dissimilar laser welding of NiTi and AISI 316L SS using a Tantalum (Ta) interlayer. It helps improving the welded joint quality. It was found that when the content of Ta was increased in the weld joint, the amount of brittle IMCs (TiFe4, TiCr2, TiFe, etc.) were decreased. Li et al. [7] considered dissimilar LW of NiTi and AISI 304 SS wires. Welding was carried out with and without presence of Co interlayer respectively. It was found that the addition of Co interlayer helped in improving tensile strength.

It has been observed that there is insufficient research on the welding ability of NiTi SMAs when combined with other materials. To address this gap, the performance of NiTi wire laser welding with both ferrous and non-ferrous materials is examined using Taguchi's methodology. Subsequently, multiple performance characteristics are optimized by applying the Utility concept.

2 Research Method

The material used is NiTi wire, stainless-steel and copper wire of 1.5mm diameter. Welding was done with laser spot welding machine. The micro-hardness of the material is measured utilizing a ZwicK/Roell ZHμ HD micro hardness tester, following the guidelines of ASTM E23. Meanwhile, the tensile test was performed using an INSTRON 3382 machine with a 100KN capacity (computer-controlled) and a crosshead speed of 1mm/min, while adhering to the ASTM E8/E8M-15a standard. The composition of the NiTi wire being tested is provided in Table 1.

Table 1. NiTi wire material composition

Ti (wt%)	Ni (wt%)	Cu (wt%)	Cr (wt%)	Fe (wt%)	Co (wt%)	Nb (wt%)	C (wt%)	O (ppm)	H (ppm)	N+O (ppm)
44.28	55.66	0.01	0.01	0.012	0.01	0.01	0.226	275	2	281

3 Results and Discussion

3.1 TAGUCHI Analysis for NiTi-SS Joining

The study utilized Taguchi analysis with Minitab17 to design an experiment (DOE) that focused on three process parameters: laser power (L), scan speed (S), and focal position (F). Three levels for each parameter were selected, and an L_9 Taguchi orthogonal array was generated. Subsequently, DOE was conducted, and the responses for NiTi-SS joining were recorded in Table 2. The S/N ratio for both micro-hardness and tensile strength was evaluated using Taguchi analysis, and the results are also reported in Table 2.

Table 3 shows the rank of the factors and optimal parameter setting for micro-hardness. For micro-hardness, focal position is rank one among independent parameters. The optimal parameter for micro- hardness was 300W laser power, 5mm/sec scan speed and 0mm focal position. This optimal parameter can be observed in main plot for S/N ratio for NiTi-SS joining (Fig 1). The optimal hardness for this parameter is calculated to be 344.367.

Table 2. DOE, responses and S/N ratios for NiTi-SS joining

L (W)	S (mm/sec)	F (mm)	Micro-hardness (Hv)	Tensile strength (MPa)	SNR micro-hardness	SNR Tensile Strength
100	5	0	340.2	1354.65	50.6346862	62.636542
100	5.5	0.5	311.68	1346.67	49.8741787	62.5852237
100	6	1	290.83	1257.67	49.2727841	61.991334
200	5	0.5	317.18	1627.78	50.0261159	64.2319142
200	5.5	1	269.74	1467.45	48.6189071	63.3312663
200	6	0	324.85	1496.8	50.2336574	63.5032755
300	5	1	321.46	1550.06	50.1425388	63.8069702
300	5.5	0	309.97	1594.78	49.8263933	64.0540156
300	6	0.5	318.29	1539.44	50.0564599	63.7472553

Table 3. Parameter ranking for micro-hardness of NiTi-SS joining

	Level				
Factor	**1**	**2**	**3**	**Delta**	**Rank**
L	314.2	303.9	**316.6**	12.6	3
S	**326.3**	297.1	311.3	29.1	2
F	**325.0**	317.5	294.0	31.0	1
Overall mean	311.7667				
Optimal Setting	L3	S1	F1		

For tensile strength, the response table is shown in Table 4. Laser power was found to be rank one. Fig 2 indicates that the ideal combination of parameters for achieving the highest tensile strength is a laser power of 300W, a scan speed of 5mm/sec, and a focal position of 0.5mm. The corresponding calculated optimum tensile strength is 1635.667.

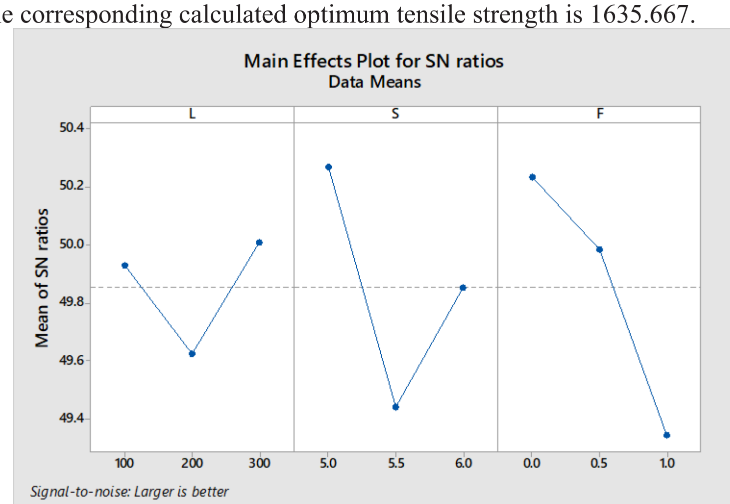


Fig. 1. Main Effects Plot of S/N Ratio for micro-hardness for NiTi-SS.

 https://doi.org/10.1051/e3sconf/202339101167

$$\mathbf{Hardness_{opt} = L_3 + S_1 + F_1 - 2 \times overall\ mean = 344.367}$$

Table 4. Parameter ranking for tensile strength of NiTi-SS joining

	Level				
Factor	**1**	**2**	**3**	**Delta**	**Rank**
L	1320	1531	**1561**	242	1
S	**1511**	1470	1431	80	3
F	1482	**1505**	1425	80	2
Overall mean	1470.667				
Optimal Setting	L3	S1	F2		

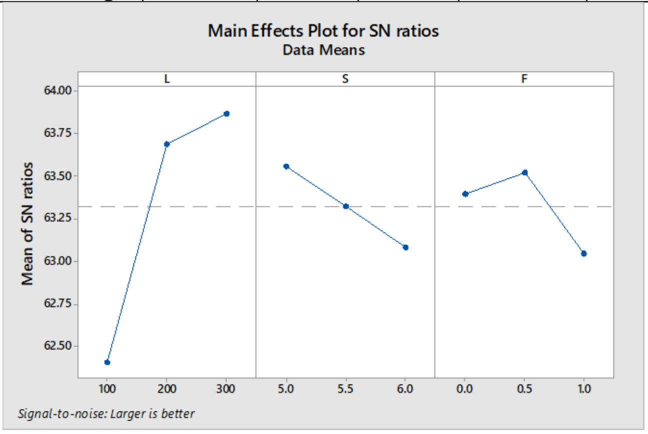


Fig. 2. Main Effects Plot of S/N Ratio of process parameters for tensile strength for NiTi-SS

$$\mathbf{Tensile\ stregth_{opt} = L_3 + S_1 + F_2 - 2 \times overall\ mean = 1635.667}$$

3.2 Taguchi Analysis for NiTi-Cu Joining

The responses and S/N ratio for both micro-hardness and tensile strength for NiTi-Cu joining are noted in Table 5.

Table 5. DOE, responses and S/N ratios for NiTi-Cu joining

L (W)	S (mm/sec)	F (mm)	Micro-hardness (Hv)	Tensile strength (MPa)	SNR for micro-hardness	SNR for Tensile strength
100	5	0	324.06	1002.20	50.21	60.02
100	5.5	0.5	333.47	1107.75	50.46	60.89
100	6	1	329.07	1163.76	50.35	61.32
200	5	0.5	328.20	1195.80	50.32	61.55
200	5.5	1	337.74	1369.38	50.57	62.73
200	6	0	337.06	1388.08	50.55	62.85
300	5	1	323.24	1386.86	50.19	62.84
300	5.5	0	329.00	1345.28	50.34	62.58
300	6	0.5	318.73	1486.47	50.07	63.44

Table 6. Parameter ranking for micro-hardness of NiTi-Cu

	Level				
Factor	**1**	**2**	**3**	**Delta**	**rank**
L	328.9	**334.3**	323.7	10.7	1
S	325.2	**333.4**	328.3	8.2	2
F	**330**	326.8	330	3.2	3
Overall mean	328.9556				
Optimal Setting	L2	S2	F1		

Table 6 and Table 7 present the rank of factors and the optimal parameter settings for micro-hardness and tensile strength, respectively. Laser power was found to be more significant than the other parameters for both micro-hardness and tensile strength. For micro-hardness, the optimal parameter setting was 200W laser power, 5.5mm/sec scan speed, and 0mm focal position, which can be observed in the main plot for S/N ratio for NiTi-Cu joining (Fig 3). The optimal micro-hardness calculated for this parameter setting was 339.789. For tensile strength, the optimal parameters were 300W laser power, 6mm/sec scan speed, and 1mm focal position, as shown in Fig 4. The optimum tensile strength calculated was 1507.379.

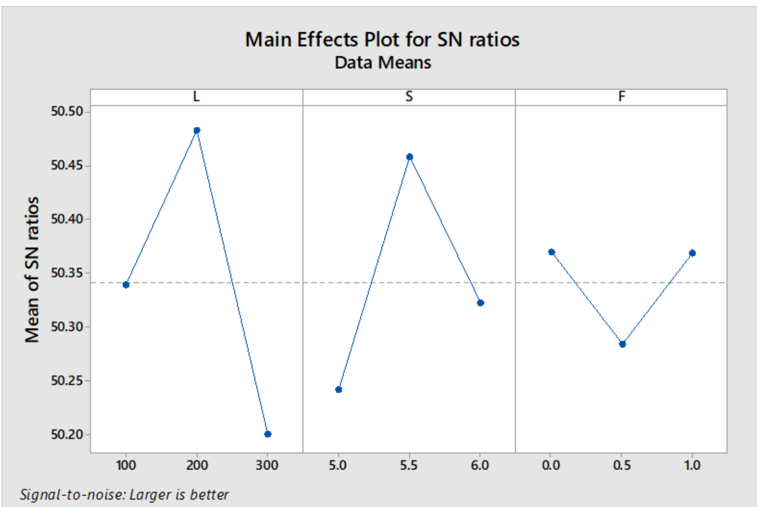


Fig. 3. Main Effects Plot of S/N Ratio of process parameters for micro-hardness for NiTi-Cu

$$\mathbf{Hardness_{opt} = L_2 + S_2 + F_1 - 2 \times overall\ mean = 339.789}$$

Table 7. Parameter ranking for tensile strength

	Level				
Factor	**1**	**2**	**3**	**Delta**	**Rank**
L	1091	1318	**1406**	315	1
S	1195	1274	**1346**	151	2
F	1245	1263	**1307**	61	3
Overall mean	1271.667				
Optimal Setting	L3	S3	F3		

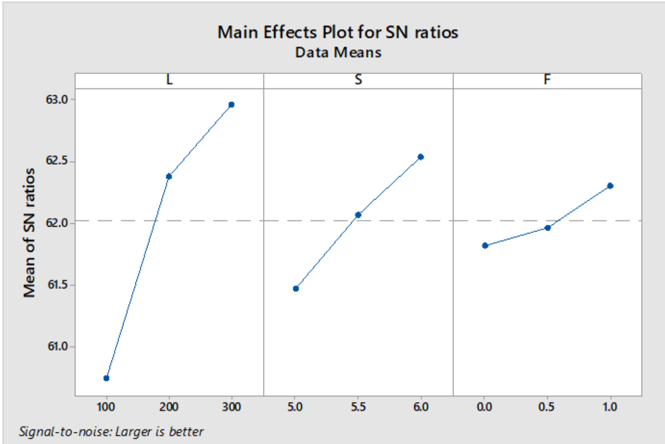


Fig. 4. Main Effects Plot of S/N Ratio for tensile strength for NiTi-Cu

$$\textbf{Tensile stregth}_{\textbf{opt}} = \textbf{L}_3 + \textbf{S}_3 + \textbf{F}_3 - 2 \times \textbf{overall mean} = \textbf{1507.379}$$

3.3 Utility Analysis

To convert single-response optimization into a multi-response analysis, the utility concept was employed. This concept involves transforming the values of individual characteristics into a single index known as overall utility. Table 8 presents the total utility for the combined responses in the case of NiTi-SS joining.

Table 8. Utility Table for NiTi-SS joining

Run	L	S	F	Utility of Hardness	Utility of Tensile strength	Overal Utility
1	100	5	0	9.962	8.691	9.326
2	100	5.5	0.5	9.125	8.621	8.873
3	100	6	1	8.463	7.812	8.137
4	200	5	0.5	9.292	10.865	10.079
5	200	5.5	1	7.743	9.638	8.691
6	200	6	0	9.520	9.872	9.696
7	300	5	1	9.420	10.286	9.853
8	300	5.5	0	9.072	10.623	9.847
9	300	6	0.5	9.325	10.205	9.765

Table 9. Parameter ranking for Overall Utility for NiTi-SS

	Level				
Factor	**1**	**2**	**3**	**Delta**	**Rank**
L	8.779	9.488	**9.822**	1.043	1
S	**9.753**	9.137	9.200	0.616	3
F	**9.623**	9.572	8.894	0.730	2
Overall mean	9.3631				
Optimal Setting	L3	S1	F1		

$$\textbf{Overall Utility}_{\textbf{opt}} = \mathbf{L_3} + \mathbf{S_1} + \mathbf{F_1} - \mathbf{2} \times \textbf{overall mean} = \mathbf{10.471}$$

After computing the overall utility, the ranks of the parameters are determined. The parameter ranking using utility data for NiTi-SS joining is presented in Table 9. It is found that laser power comes in rank one for this joining. Second rank is focal position and third is scan speed. The optimal parameter for the overall utility is evaluated with the help of S/N plot (Fig 5 (a)). The optimal parameter is 300W laser power, 5mm/sec scan speed and 0mm focal position. The optimal overall utility for NiTi-SS joining was calculated to be 10.471.

Overall utility for NiTi-Cu joining is noted in Table 10 along with the utility of hardness and tensile strength. This overall utility is then optimized and the response table is shown in Table 11. In Table 11 parameter ranking and the optimal parameter combination for NiTi-Cu joining with utility concept was noted.

Table 10. Utility Table for NiTi-Cu joining

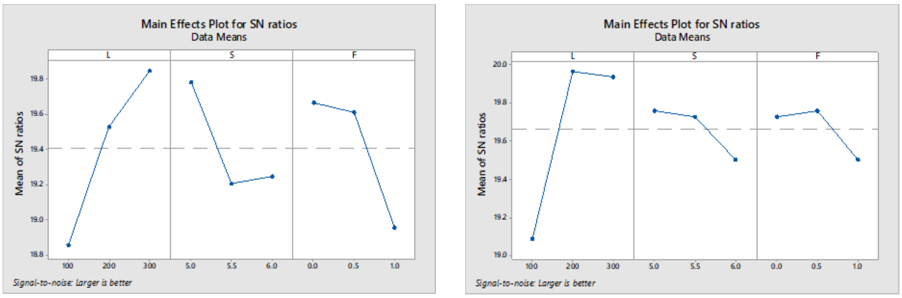
Run	L	S	F	Utility of Hardness	Utility of Tensile strength	Overall Utility
1	100	5	0	9.497	8.691	9.094
2	100	5.5	0.5	9.771	8.621	9.196
3	100	6	1	9.644	7.812	8.728
4	200	5	0.5	9.618	10.865	10.242
5	200	5.5	1	9.892	9.638	9.765
6	200	6	0	9.873	9.872	9.873
7	300	5	1	9.473	10.286	9.879
8	300	5.5	0	9.641	10.623	10.132
9	300	6	0.5	9.338	10.205	9.772

The power factor was found to be the most influential parameter for the NiTi-Cu joining laser. The optimization analysis yielded an optimal parameter setting of 200W laser power, 5mm/sec scan speed, and 0.5mm focal position, which is supported by the main effect plot for S/N ratio and mean (Fig 5). The optimal overall utility for the NiTi-Cu joining process was determined to be 10.171.

Table 11. Parameter ranking for Overall Utility for NiTi-Cu

	Level				
Factor	**1**	**2**	**3**	**Delta**	**Rank**
L	9.006	**9.960**	9.928	0.954	1
S	**9.738**	9.698	9.457	0.281	2
F	9.700	**9.736**	9.457	0.279	3
Overall mean	9.6311				
Optimal Setting	L2	S1	F2		

$$\textbf{Overall Utility}_{\textbf{opt}} = \mathbf{L_2} + \mathbf{S_1} + \mathbf{F_2} - \mathbf{2} \times \textbf{overall mean} = \mathbf{10.171}$$



(a) (b)

Fig. 5. Main Effects Plot of S/N Ratio for utility for (a) NiTi-SS, (b) NiTi-Cu welding

3.4 Confirmation Test

After determining the optimal setting parameters using optimization analysis, experiments were conducted to record the resulting responses. The recorded values were compared with the predicted values, and the errors were calculated. The percentage error was less than 4%, suggesting that the optimal parameter settings are acceptable. In addition, based on the confirmation test, the Utility-based optimized parameter combination was found to perform better than the Taguchi-based optimized parameter combination. The results of the comparison are presented in Table 12 and Table 13.

Table 12. Confirmation Test for Utility based Optimum parameter

Type of Materials	Optimum process parameter	Responses	Predicted Value	Experimental Result	% error
NiTi-SS	L3-S1-F1	Micro-hardness	332.82	321.34	3.57
		Tensile Strength	1611.29	1549.73	3.97
NiTi-Cu	L2-S1-F2	Micro-hardness	340.61	343.45	0.82
		Tensile Strength	1479.37	1459.13	1.38

Table 13. Confirmation Test for Taguchi based Optimum parameter

Type of Materials	Optimum process parameter	Responses	Predicted Value	Experimental Result	% error
NiTi-SS	L3-S1-F1	Micro-hardness	344.367	321.34	7.1
	L3-S1-F2	Tensile Strength	1635.667	1549.73	5.5
NiTi-Cu	L2-S2-F1	Micro-hardness	339.789	343.45	1.06
	L3-S3-F3	Tensile Strength	1507.379	1459.13	3.3

4 Conclusion

In this research the weldability of NiTi wire with dissimilar ferrous and non-ferrous wires is investigated. The optimal parameter setting for individual output was determined by Taguchi analysis. The multi response analysis was performed with the help of Utility concept and combined optimal parameter was obtained. The results obtained were as followed;

- When joining NiTi and SS materials, the optimal parameters for micro-hardness were determined to be a laser power of 300W, a scan speed of 5mm/sec, and a focal position of 0mm. The micro-hardness was found to be highest at this focal position. On the other hand, when considering ten-sile strength, the laser power was found to be the most influential parameter. The optimal parameters for achieving the highest tensile strength were a laser power of 300W, a scan speed of 5mm/sec, and a focal position of 0.5mm.
- When joining NiTi and Cu, the most significant parameter for both micro-hardness and tensile strength is the laser power, compared to other parameters. The best combination of parameters for achieving optimal results were found to be 200W laser power, a scan speed of 5.5mm/sec, and a focal position of 0mm. For optimal tensile strength, the combination of parameters was 300W laser power, a scan speed of 6mm/sec, and a focal position of 1mm.
- Analysis of overall utility showed that laser power is placed at rank one for both NiTi-SS and NiTi-Cu joining.
- Analysis of confirmation test showed improvement in values of responses for Utility based optimization than Taguchi analysis.
- Confirmation test results verifies that the optimum parameter obtained are feasible.

References

1. D. B. K. T., S. P., and R. T.: Experimental investigation and characteriza-tion of laser welded NiTinol shape memory alloys. Journal of Manufac-turing Processes 25, 253–261 (2017).
2. Kramár, T., Tauer, J. and Vondrous, P.: Welding of nitinol by selected technologies. Acta Polytechnica 59, 42–50 (2019).
3. Oliveira, J. P., Miranda, J. P. and Fernandes, F. M.B.: Welding and Join-ing of NiTi Shape Memory Alloys: A Review. Progress in Materials Sci-ence 88, 12–466 (2017).
4. Mehrpouya, M., Gisario, A. and Elahinia, M.: Laser welding of NiTi shape memory alloy: A review. Journal of Manufacturing Processes 31, 162–186 (2018).
5. Zeng, Z., Oliveira, J. P., Yang, M., Song, D. and Peng, B.: Functional fa-tigue behavior of NiTi-Cu dissimilar laser welds. Materials & Design 114, 282–287 (2017).
6. Ng, C. H., Mok, E. S. H. and Man, H. C.: Effect of Ta interlayer on laser welding of NiTi to AISI 316L stainless steel. Journal of Materials Pro-cessing Technology 226, 69–77 (2015).
7. Li, H., Sun, D., Cai, X., Dong, P. and Gu, X.: Laser welding of TiNi shape memory alloy and stainless steel using Co filler metal. Optics Laser Technology 45, 453–460 (2013).