MECHANICAL AND METALLURGICAL CHARACTERIZATION OF DISSIMILAR FSW JOINTS OF MONEL 400 AND SS316L

G. VENKAT RAMANA[1], NARSIMHULU SANKE[2]

[1,2] Department of Mechanical Engineering, University College of Engineering, Osmania University, Hyderabad, Telangana 500007, India

Abstract: Modern structural conception demands the best mechanical properties irrespective of inhomogeneities that arise due to the usage of different metal alloy combinations along with other properties such as corrosion resistance and high strength. Nickel based high strength alloys Monel 400 and austenitic steel SS316L are in use for specific application in chemical and power plants that requires heat and fatigue resistance to the weldments. Friction Stir Welding (FSW), a solid-state welding process could be one another option for welding dissimilar combinations of base materials owing to its ability to produce homogenous weldments. In the present work, Tungsten Carbide (10% Co) tool with conical tipped profile having dimensions of 2.8mm lengths for welding base plates of 3mm were considered to produce weld joints. Welds were made with the FSW process parameters 800 rpm and feed rates of 25 mm/min to 35 mm/min. The obtained weld coupons were tested to find the tensile properties and the same were observed under OM and SEM for homogeneity in microstructure. EDAX point analysis was made to see the possibility of WC inclusion.

Key Words**:** FSW, Monel 400, SS316L, Tensile Test, OM, EDAX.

1. INTRODUCTION

Nickel-Copper alloys exhibit resistance to high temperature and corrosive environments. One such alloy Monel 400 with excellent fatigue resistance at high temperatures has applications in a wide variety of media that sustains corrosion environments also has good weldability and moderate to high strength. Austenitic stainless steels are well known for applications requiring corrosion resistance in moderately corrosive environments. SS316/316L is a chromium-nickel molybdenum alloy that resists moderately oxidizing and reducing environments is one such among austenitic steels that also has good weldability. Dissimilar Combination of Monel 400 and AISI 316 has wide range of applications in boiler feed water tubes, propeller shafts petrochemical equipment where in the weld roots undergo interaction with hot corrosive environment [1]. FSW also has potential in joining similar and dissimilar metals of high strength such as Titanium, Steels and Ni based alloys. FSW Weldments obtained from FSW technique produces fine grained structures with low interface effects in dissimilar weldments which would enhance the properties of weld joints. FSW tool material and profile geometry effects the quality of the weld structures (suitable tool materials for welding high strength materials [4]: WC, WC with 10% Co, WC with Lanthanum, PCBN).

In FSW, the joining mechanism of base metal involves the softening and mixing of base metals by the frictional heat produced because of the relative contact motion of the tool pin surface with base metal and heat produced due to severe plastic deformation [2] [7]. To ensure the solid-state welding and the temperature distribution across the tool materials limit in the process parameters and their effect to reach the temperatures less than the melting point is desired. Comparing the properties of welds obtained from fusion welding process, that has minor metallurgical defects induced in the weldments, with fsw can be choice to overcome defects [3]. The researchers have tried one sided butt joint for 2 mm sheets for joining hard metals involving super-alloys and steels. For plate thickness above 2 mm i.e., 3 to 4 mm plates much attention is not given due to the restriction in the tool material and profile design [6]. Researchers have done work on joining dissimilar combination of Ni-based alloys and stainless steels with fusion welding processes but have reported in-homogeneity in the weldments and wider bead geometries with coarse grain structures [9][10].

The objective of this work is to find suitable material and tool dimensions for successfully joining high strength alloy Monel 400 and AISI 316L, dissimilar combination plates 3mm using FSW technique of dissimilar FSW. Considering the heat generated due to friction and plastic deformation of the materials during the process that would ensure the solid-state temperatures in the FSW process metallurgical tests were to be performed to identify the homogeneity in the weld zones.

2. Materials and Experimentation

Table 1 Chemical composition of Monel 400 and SS316L in wt. percentage

Base Metals	Fe	Cr	Ni	Cu	Mo	Mn	Si	C	Others
SS316L	66.41	17.6	10.6	Nil	2.5	2.0	0.8	0.08	P-0.004

Monel 400	2.5	Nil	63.15	31.65	Nil	2.0	0.5	0.3	Nil

Table 2 Mechanical properties of Monel 400 and SS316L base metals

Base Metals	UTS, MPa	Yield strength, MPa	Modulus of Elasticity (E), GPa	Elongation in %	Microhardness value, $HV_{0.1}$
Monel 400	516	215	179	34	160
SS316L	532	350	192	44	198

In the present experimentation dissimilar combinations of Monel 400 and SS316L plates with 3-mm thick were joined using. The chemical compositions in percent by weight and their mechanical properties are given in Tables 1and 2, respectively. The base metals Monel 400 and SS 316L were polished and etched to identify the as given base metal microstructures. Equiaxed grains and coarse grain of austenite were observed Monel400 and SS316L as shown in Fig 4a and 4g. The WC tool with 10% Cobalt was used to join the base metals. The dimensions of the tool were taken after considering the material flow over the tool pin. The shoulder of 20 mm in diameter, the pin length of 2.8 mm with 0.2mm less than the plate thickness was machined with diamond grinder while maintaining a conical interface between the tip and the shoulder base. Profile tip base along the shoulder was machined conical from 6 mm diameter at the root to 3 mm at the tip, as shown in Fig. 2. Fig 1. Argon gas was used to shield the weld zone and pin tip across the weld line to present the zone from external oxidation. The FSW joints were developed using the rotating speed of 800rpm and feed rate of 25,30 and 35 mm/min. Butt joints were obtained as shown in Fig 3 by keeping the weld plates side by side with enough clamping force and base clearance to resist macro distortions caused by tool motion as shown in fig 5. with Monel400 on advancing side. The machine was set to a tilt angle of 0° and given a plunge of 3 mm along vertical direction.

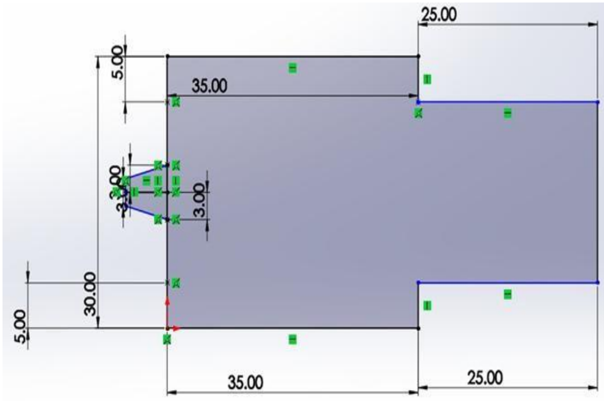


Fig. 1: FSW tool dimensions CAD diagram **Fig 2:** FSW tools machines with diamond grinder

Fig. 3: FSW dissimilar welded joints of Monel 400 and SS 316L and tool wear.

2.1 Characterization procedure

Samples were cut using W-Electro-discharge machining having the weld beads shown in the middle of the samples. ASTM E8 standard was considered in specimens for conducting tensile test as shown in fig 4 with displacement of 1 mm/min under room temperature. Micro hardness around the weld zone was measured at an interval of 0.25 mm. Indentations were made by levering 500 g of load with a dwell time of 15 s for each measurement. Optical microscope was used to take macrographs and SEM with EDS (energy dispersive spectroscopy) was used for conducting point analysis to find weld composition. Samples of 10*10 were W-EDM cut across the weld cross sections in the same weld coupons in transverse direction as shown in Fig. 3.8 for further metallographic analysis. These samples were initially polished using 400, 800, 1000, 1500, and 2000 emery papers and later mirror-polished with 1 μm diamond paste on a buffing cloth.

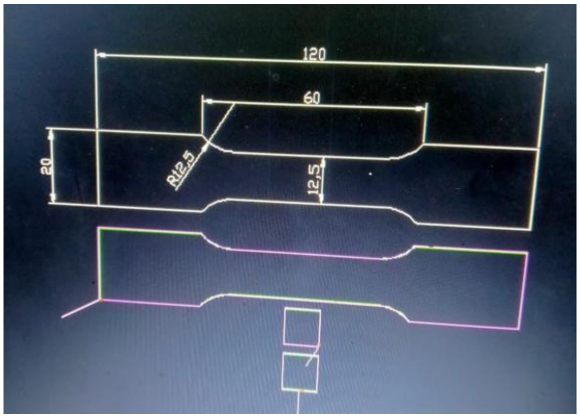


Fig 4: UTM Specimen as per ASME E8 **Fig 5:** Specimen and tool holder

3. Results and Discussions

Tensile test: Figure 6 presents the stress-strain graph of dissimilar joints obtained at 800 rpm rotating speed with 25 and 30 mm/min feed rate (S1 and S2). Similarly, stress-strain graph for specimen welded at 800rom and 35 mm/min feed is shown in fig 8. The results obtained from the tensile tests are shown Table 3. Results of S1 and S2 shown a lower tensile strength than that of S3 which was welded with the spindle speed of 800 rpm and feed of and 35 mm/min. It is observed that at constant rotating speed, the tensile strength of the joints has increased with increasing the feed rate. Weld made with machine feed of 35mm/min has shown higher strength.

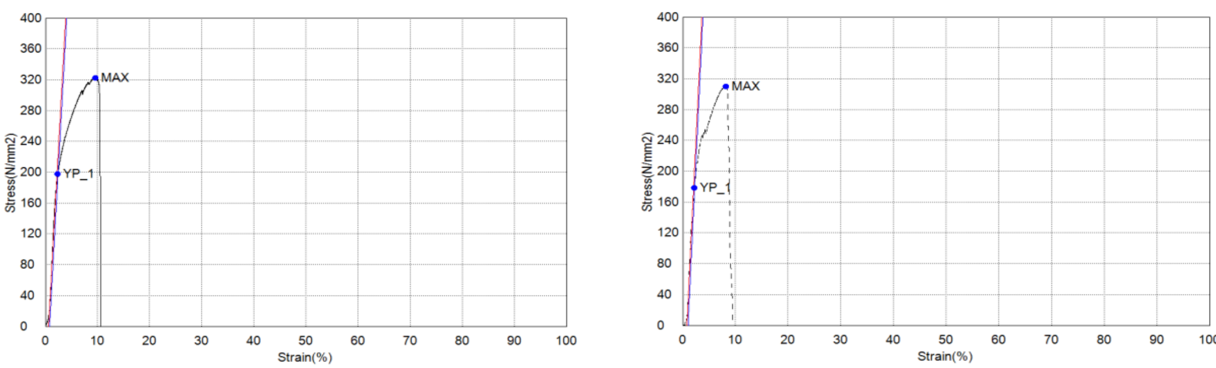


Fig 6: Stress- strain graph of specimens S1 and S2

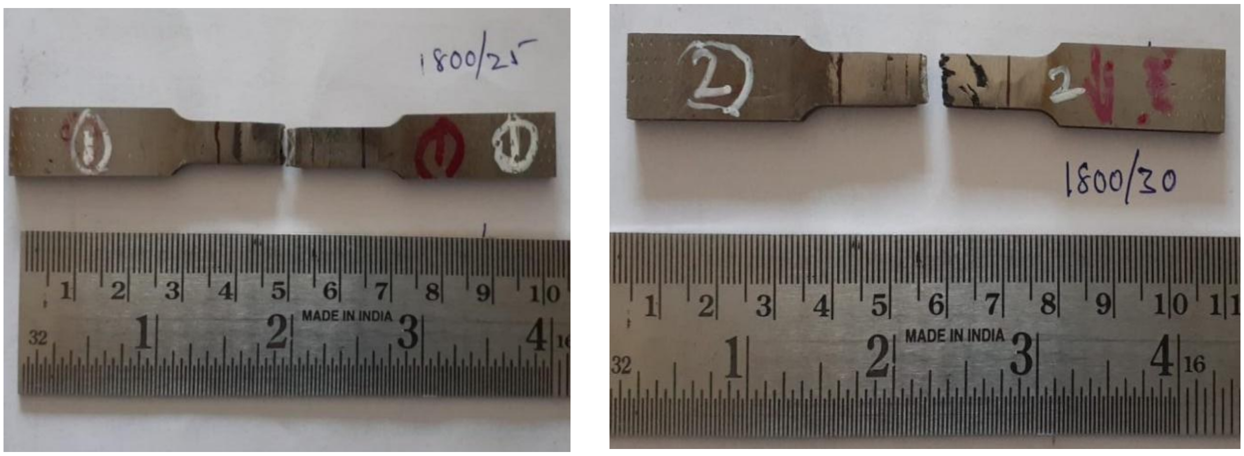


Fig 7: Failed under UTM specimens S1 and S2

Fig 8: UTM results of S3 and FSW joint of Monel 400 vs SS 316L

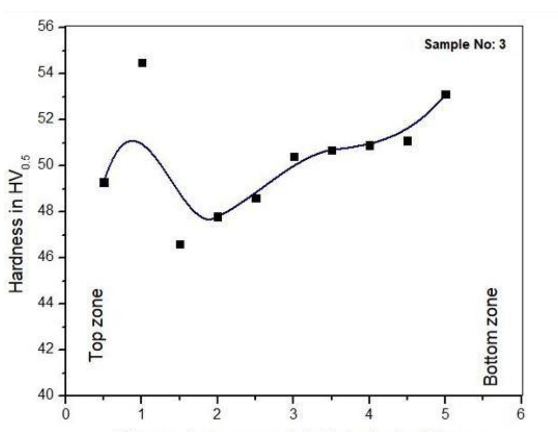


Fig 8b: Vickers hardness variation from top to bottom along SZ.

A vertical hardness profile was drawn to see the variation of values from top to bottom which would give the possibility of uniformity across the weld line. This result would give us an idea of material distribution and intermixing at the center weld line. As shown in the fig 8b there is almost a variation of +/- 5 units and almost remaining same showing the intermixing at the interface.

3.3. Metallurgical studies

The four distinct regions that are formed in the FSW are the nugget or stirred zone (SZ), the thermo-mechanically affected zone (TMAZ), and the heat affected zone (HAZ) and the base metal (BM). The optical images of the full joint is shown in Fig 9 with illustration of various zones named as A, B, C, D, E, F, G, and H as Monel 400 base, TMAZ, HAZ, SZ, HAZ, TMAZ and SS316L respectively. In the fig, coloured zone is Monel 400 and light zone is SS 316L. A complete intermixing of base metals can be seen in S3 obtained at the feed rate of 35 mm/min and 800 rpm. Fig 9 C and F showing a TMAZ which distinguished as the grains are changing their size gradually toward the shar zone. TMAZ-SZ interface on either side are clearly visible due to the dissimilarity in base metals and a slight asymmetry can be visualized. According to Fig. 9D, E and F, the TMAZ has shown severely deformed grains orientated perpendicularly to the original grains. The EDX results on base metals and nugget zones are shown in Fig 12, 13 and 14 with Monel 400, nugget and SS316L side respectively. According to the EDX results, these particles (containing Ni (63.35wt%), Cu(30.2wt%) and Fe(2.23wt%) are observed on Monel 400 side and mostly Fe(3=68.01 wt%), Cu(18.02wt%), Ni(9wt%) on the SS 316L side. Near the nugget zone i.e', SZ combination of Fe,Cu and Ni can be seen as shown in Fig 14.

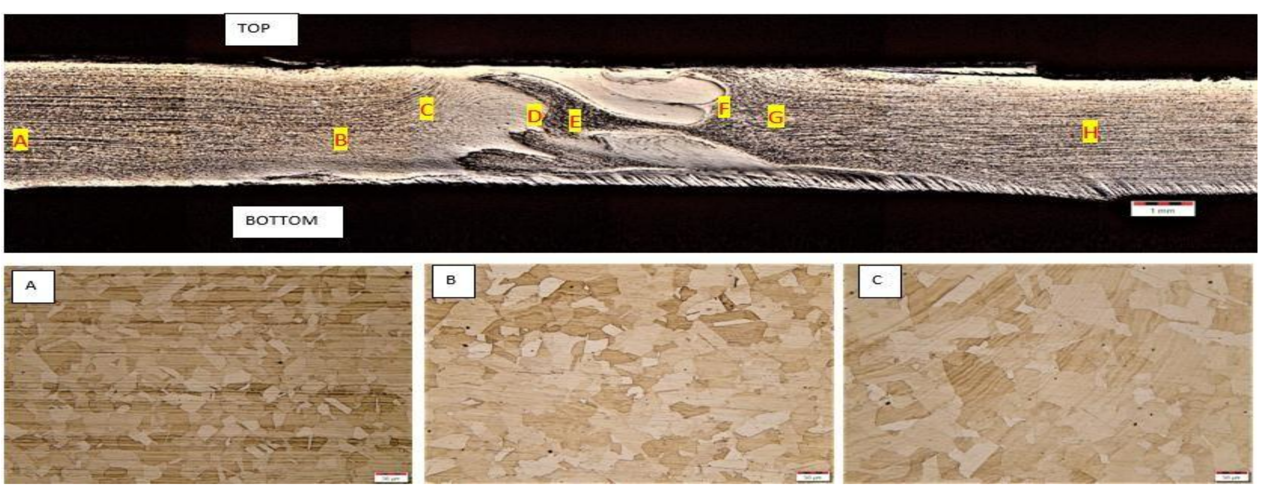


Fig.9: Macrostructure of weldment and Microstructures of Monel400 side

Fig.10: macrostructure of weldment HAZ and TAZ zones

Fig.11: Trial 2 macrostructure of weldment on AISI 316L side

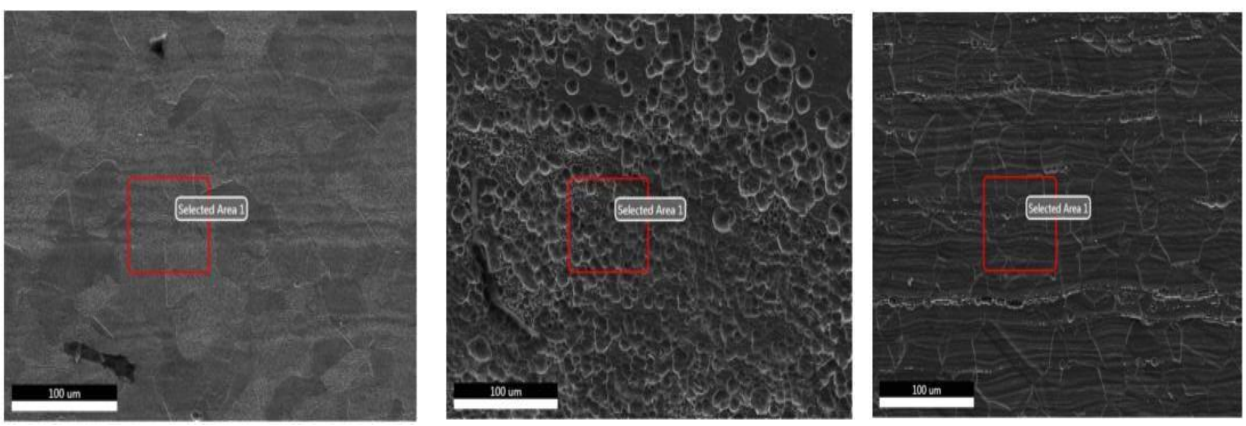
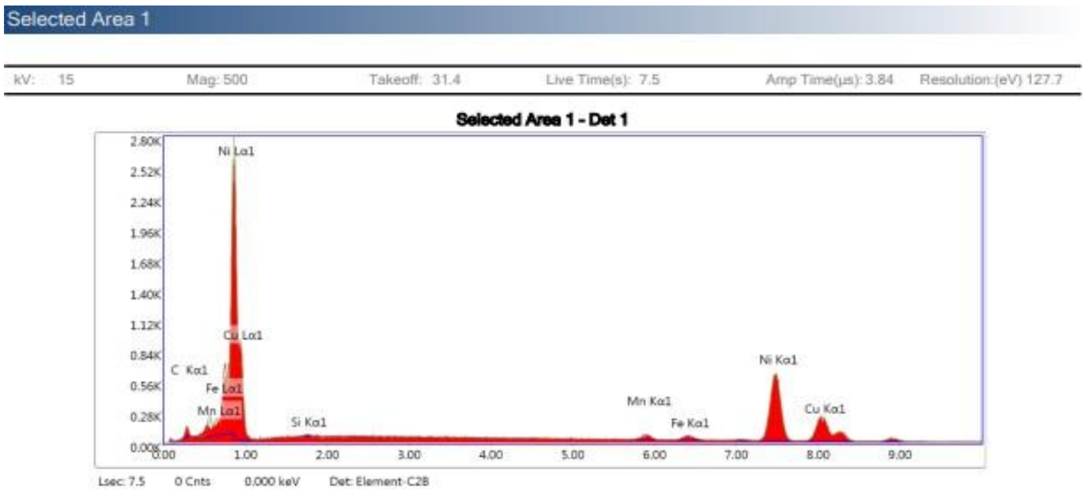


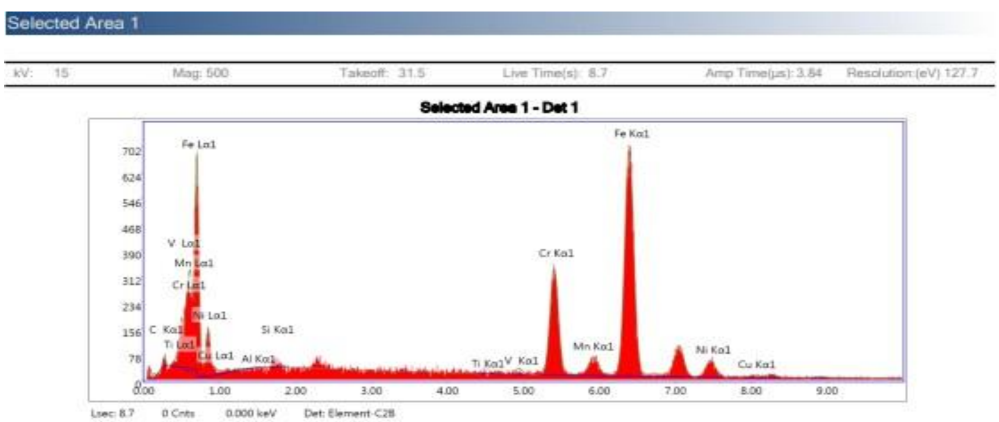
Fig 12: EDAX point images on zones A(Monel 4000), E (Weld zone) and H (SS 316L)



eZAF Smart Quant Results

Element	Weight %	Atomic %	Net Int.	Error %	Kratio	Z	A	F
C K	2.44	11.11	59.46	20.98	0.0061	1.3466	0.1851	1.0000
SiK	0.17	0.33	15.48	69.06	0.0010	1.1741	0.4869	1.0019
MnK	2.16	2.15	83.99	21.50	0.0238	0.9797	0.9905	1.1324
FeK	2.05	2.01	69.87	26.36	0.0236	0.9958	0.9947	1.1608
NiK	60.47	56.28	1236.23	4.23	0.6178	1.0067	0.9968	1.0181
CuK	32.71	28.13	487.27	6.31	0.3115	0.9559	0.9942	1.0022

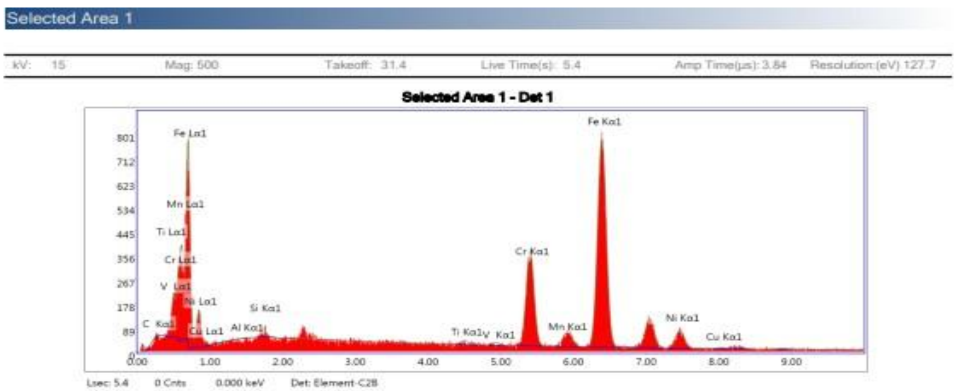
Fig 13: EDAX point images on zones A Monel 400



eZAF Smart Quant Results

Element	Weight %	Atomic %	Net Int.	Error %	Kratio	Z	A	F
C K	0.95	4.19	17.44	34.54	0.0030	1.3503	0.2332	1.0000
AlK	0.04	0.09	2.14	99.99	0.0002	1.1506	0.4352	1.0017
SiK	0.40	0.76	25.71	38.57	0.0027	1.1761	0.5629	1.0029
TiK	0.66	0.73	24.41	33.20	0.0071	1.0087	0.9788	1.0815
V K	0.69	0.72	21.36	45.70	0.0074	0.9842	0.9875	1.1026
CrK	19.05	19.49	508.76	5.06	0.2037	0.9992	0.9924	1.0780
MnK	1.43	1.39	31.20	35.16	0.0147	0.9783	0.9932	1.0600
FeK	67.64	64.43	1174.20	3.89	0.6628	0.9939	0.9761	1.0101
NiK	7.96	7.22	90.18	17.26	0.0752	1.0034	0.9356	1.0063
CuK	1.17	0.98	10.01	69.63	0.0107	0.9520	0.9497	1.0099

Fig 14: EDAX point images on zones E (Weld zone)



eZAF Smart Quant Results

Element	Weight %	Atomic %	Net Int.	Error %	Kratio	Z	A	F
C K	0.28	1.25	8.57	84.25	0.0009	1.3532	0.2306	1.0000
AlK	0.02	0.04	1.53	99.99	0.0001	1.1531	0.4316	1.0017
SiK	0.40	0.77	42.93	36.34	0.0026	1.1787	0.5594	1.0029
TiK	0.52	0.60	33.00	62.53	0.0056	1.0111	0.9782	1.0816
V K	0.37	0.39	19.31	67.55	0.0040	0.9865	0.9870	1.1044
CrK	18.68	19.59	850.63	5.06	0.2004	1.0016	0.9923	1.0795
MnK	1.33	1.32	49.70	36.20	0.0138	0.9807	0.9936	1.0622
FeK	68.44	66.82	2026.20	3.79	0.6732	0.9963	0.9767	1.0109
NiK	9.30	8.64	179.22	15.94	0.0880	1.0060	0.9353	1.0058
CuK	0.66	0.57	9.65	68.22	0.0061	0.9546	0.9493	1.0097

Fig 15: EDAX point images on zones H (SS 316L)

Table 4: UTM test results of FSW weld joints of Monel 400 and SS 316L

Specimen No	Tool speed (rpm)	Feed rate (mm/min)	Y.S, MPa	UTS, MPa	% of Elongation
S1	1800	25	197	323	7.8
S2	1800	30	170	314	9.1
S3	1800	35	262	509	19.3

CONCLUSIONS

- Specimen welded with 6mm to 3mm have produced sound welds because of better mixing at higher temperatures and flow of the materials around the pin.
- FSW specimen joined with 800 rpm and 35mm/min feed has given best result of UTS 504MPa

- Vickers hardness numbers plotted vertically alongside of the weld center has shown a deviation of 5 units confirming the homogeneity in mixing.
- From macroscopic optical imaging, inter mixing can be seen between Monel 400 and SS316L.

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