

Strength and Microstructural Analysis of Bi-Metallic Rotary Friction Welds between Stainless Steel 304 and 316

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ABSTRACT

This study focused on assessing bi-metallic rotary friction welded joints between stainless steel 304 and 316. Various process parameters were adjusted for welding, including rotational speed (692, 832, 1228 rpm), burn-off length (6, 9, 12 mm), and forge time (30-40, 40-50, 50-60 seconds). The experiment was designed using an Orthogonal array L9. The aim was to analyze the strength and microstructure of the welded joints, employing tests such as tensile strength, Vickers micro-hardness, SEM, and EDS analysis. The results revealed that the highest tensile stress (456.58 MPa) and hardness value (331 HV) were attained at a rotational speed of 1228 rpm, a burn-off length of 12 mm, and a forge time of 40-50 seconds. SEM images indicated brittle fracture, attributed to elevated levels of carbon and phosphorus. Additionally, a signal-to-noise ratio test was conducted to assess the significance of process parameters, revealing that burn-off length and spindle speed were the primary influencing factors, while forge time remained insignificant.

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1. INTRODUCTION

In today's world, industries are opting large variety of material combination to make the product economic and efficient. Stainless steel alloys are the most important and commonly used alloys used in industries due to its better mechanical and metallurgical properties [1]. Stainless steel hardness and much corrosion

resistant make it primary choice in manufacturing industries. Stainless Steel 304 and 316 stand out as prevalent types of austenitic stainless steel. Stainless Steel 304 is characterized by its elevated nickel content, typically ranging between 8 to 10.5 percent by weight, along with a substantial chromium presence, approximately 18 to 20 percent by weight. Notable alloying elements also include

manganese, silicon, and carbon. The remainder of the chemical composition is primarily iron [2]. The high amounts of chromium and nickel give stainless steel 304 excellent corrosion resistances. Common applications of stainless steel 304 include Appliances such as refrigerators and dishwashers, Commercial food processing equipment, Fasteners, Piping, Heat exchangers, Structures in environments that would corrode standard carbon steel. Whereas stainless steel 316 has high amount of chromium and nickel and it also contain silicon, manganese, and carbon, with the majority of the composition being iron. A major difference between 304 and 316 Stainless steel is the chemical composition, with 316 containing a significant amount of molybdenum; typically, 2 to 3 percent by weight verses only trace amounts found in 304. The higher molybdenum content results in increases corrosion resistances [3]. Stainless steel alloy 316 is often considered one of the most suitable choices when selecting an austenitic stainless steel for marine applications. Other common applications of stainless steel alloy 316 include chemical processing and storage equipment, refinery equipment, medical devices, marine environments, especially those with chlorides present.

Although much variety of welding techniques available to weld stainless steels but fusion welding techniques like TIG welding, resistance welding and MIG welding are most commonly used. However, there are many problems which

are associated with the fusion welding of stainless steels such as inclusion of impurities, high brittleness and micro-structural change at the fused zone. A new microstructure developed is similar to the structure develop in case of casting. The use of solid state welding method like friction welding is the alternative instead of fusion welding techniques to avoid or reduce the adverse effects associated with fusion welding methods. Friction welding technique is commercially used to join various aero engine parts like blisk assemblies in turbine, compressor rotor and wheel etc [4,5].

2. EXPERIMENTAL PROCEDURE

The materials used in this study are SS304 and SS316. It is a T-300 series austenitic stainless steels. The chemical composition was tested on a global discharge spectrometer (Model: GDS 500A, Leco, USA). The observed and standard composition of both materials is shown in Table 1. A continuous drive rotary friction welding machine was used to fabricate weld between ss304 and ss316 round bar of 15 mm diameter. Three welding process parameters chosen after studying published literature, availability of experimental setup and conducting trial experiments were as follows: spindle speed 632, 832 and 1228 rpm, forge time range 30-40, 40-50 and 50-60 seconds and burn-off length 6, 9 and 12mm. The design of experiment used is Taguchi Technique. Table 2 shows Experimental layout of the L9 Orthogonal Array (OA).

Table 1. Composition of SS 316 and SS 304 (weight %).

Element Percentage	Standard Composition of SS 316	Observed Composition of SS 316	Standard Composition of SS304	Observed Composition of SS 304
Carbon	0.08 Max	0.040	0.08 Max	0.069
Manganese	2.00 Max	1.78	2.00 Max	1.53
Sulphur	0.03 Max	0.001	0.03 Max	0.001
Silicon	1.00 Max	0.64	1.00 Max	0.81
Phosphorous	0.045 Max	0.031	0.045 Max	0.040
Chromium	16.0 - 18.0	17.20	18.0 - 20.0	18.882
Nickel	10.0 - 14.0	10.18	8.0 - 10.50	9.52
Molybdenum	2.00 - 3.00	2.11	Nil	Nil

3. RESULTS AND DISCUSSION

3.1 Tensile Strength Analysis

Tensile test was performed on Universal Testing Machine made by “HEICO” (Hydraulic and Engineering Instruments company) having a capacity of applying 600KN load. In this test, the

specimens were subjected to axial tensile load till its fracture occurs. On the basis of the result obtained from the test, stress versus strain graphs has been plotted. The graphs were plotted at different rotational speeds at three different burn-off lengths.

Table 2. Experimental layout and Tensile strength test results.

Experiment Number	Rotational Speed (rpm)	Burn-off Length (mm)	Forge Time (Seconds)	Peak Load (KN)	Peak Displacement (mm)	Peak Stress (MPa)	Peak Strain (%)
1	692	6	30 - 40	29	4.24	236.45	8.48
2	692	9	40 - 50	37	5.01	301.67	10.02
3	692	12	50 - 60	49	6.78	399.51	13.56
4	832	6	40 - 50	34	4.56	277.21	9.12
5	832	9	50 - 60	40	5.33	326.13	10.66
6	832	12	30 - 40	52	6.92	423.97	13.84
7	1228	6	50 - 60	35	6.07	285.36	12.14
8	1228	9	30 - 40	46	6.59	375.05	13.18
9	1228	12	40 - 50	56	6.23	456.58	12.46

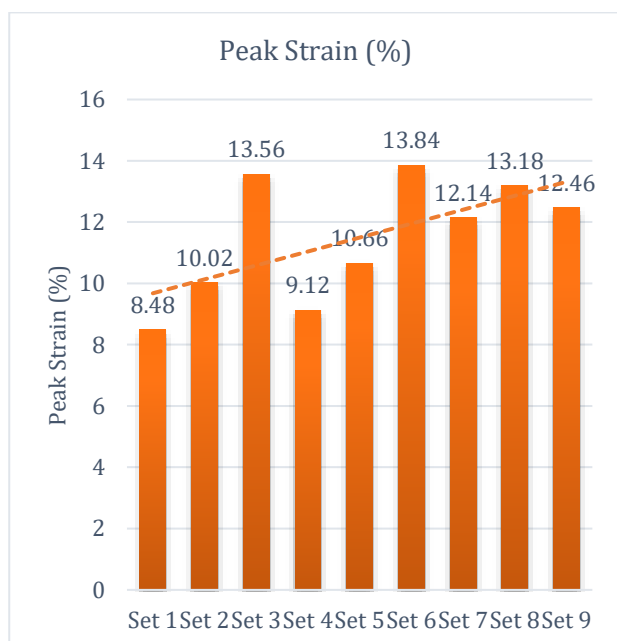
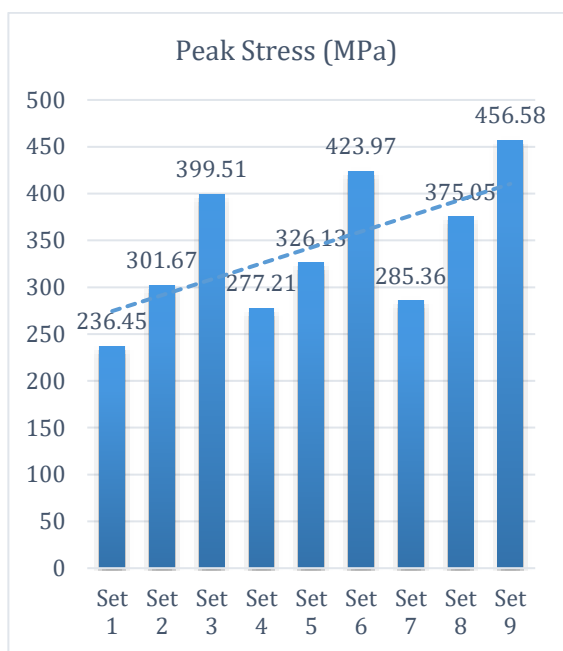


Fig 1. Variation of Peak Stress and Peak Strain for each set.

In Fig. 1, It was observed that the value of stress and strain increased and reached on the peak values that are 236.45 MPa, 277.21 MPa and 285.36 MPa whereas the strains were 8.48%, 9.12% and 12.14% at 6 mm burn-off length as we increased the rotational speed. The similar trend of values of stress i.e. 316.7 MPa, 326.13 MPa, 375.05 MPa and strains 10.02%, 10.66% and 13.18% at 9 mm burn-off length and the values of stress 399.51 MPa, 423.97 MPa and 456.58 MPa and strains 13.56%, 13.84% and 12.46% at 12 mm burn-off length was observed. All plots show necking behaviour before getting failed at the interface. Overall it was perceived that the rotation speed effect stress and strain as the highest rotation speed has highest level of stress [6]. This might be attributed that with the increase in rotational speed and burn-off length, more mass was thought to be transferred at the interfaces. Moreover [7] use tungsten inert gas welding (TIG) process to weld dissimilar stainless-steel SS 304 and SS 316 by using filler material 316L. The tensile test is performed on the sample and the ultimate tensile stress found out is 435.70 MPa where as in present work, ultimate tensile stress was found 456.58 MPa for the same set of materials with the help of rotary friction welding.

3.2 Micro-hardness Analysis

The micro hardness testing was obtained Vickers hardness tester of "FIE" (Fuel Instrument & Engineering Pvt. Ltd, Model VM50, maximum capacity 50kgf) was used. The hardness values on both side at a distance of 1 mm apart in the axial direction were measured till four readings and the hardness were also measured at the weld interface. Table 3 shows variation of Vickers micro-hardness at 692, 832, 1228 rpm respectively. It has been observed that AISI SS

316 shows a lesser amount of hardness as compare to AISI SS 304 in all samples. Micro-hardness values observed in the joints were much higher than that of the parent materials. The hardness value is maximum at the weld line for all the welded samples and decline towards

the main materials as shown in Fig. 2. The weld interfaces exhibited the highest level of hardness in nearly every scenario, likely due to the elevated temperatures generated at the rubbing surfaces, impacting their mechanical properties [6].

Table 3. Variation of Vickers micro-hardness for all sets.

Rotational Speed (RPM)	Burn-off Length (mm)	Micro-Hardness at a distance (mm) from weld towards SS 304				Micro-Hardness at weld interface	Micro-Hardness at a distance (mm) from weld towards SS 316			
		6	9	12	15		6	9	12	15
692	6	198	205	221	231	273	181	170	168	162
692	9	203	211	227	234	280	189	181	170	166
692	12	212	217	239	245	289	199	190	177	171
832	6	200	218	232	240	281	197	188	181	175
832	9	209	224	236	247	289	206	194	183	177
832	12	217	233	245	253	298	211	200	189	184
1228	6	203	233	250	259	307	221	199	187	180
1228	9	214	252	269	278	323	238	212	201	189
1228	12	225	264	273	284	331	252	239	211	198

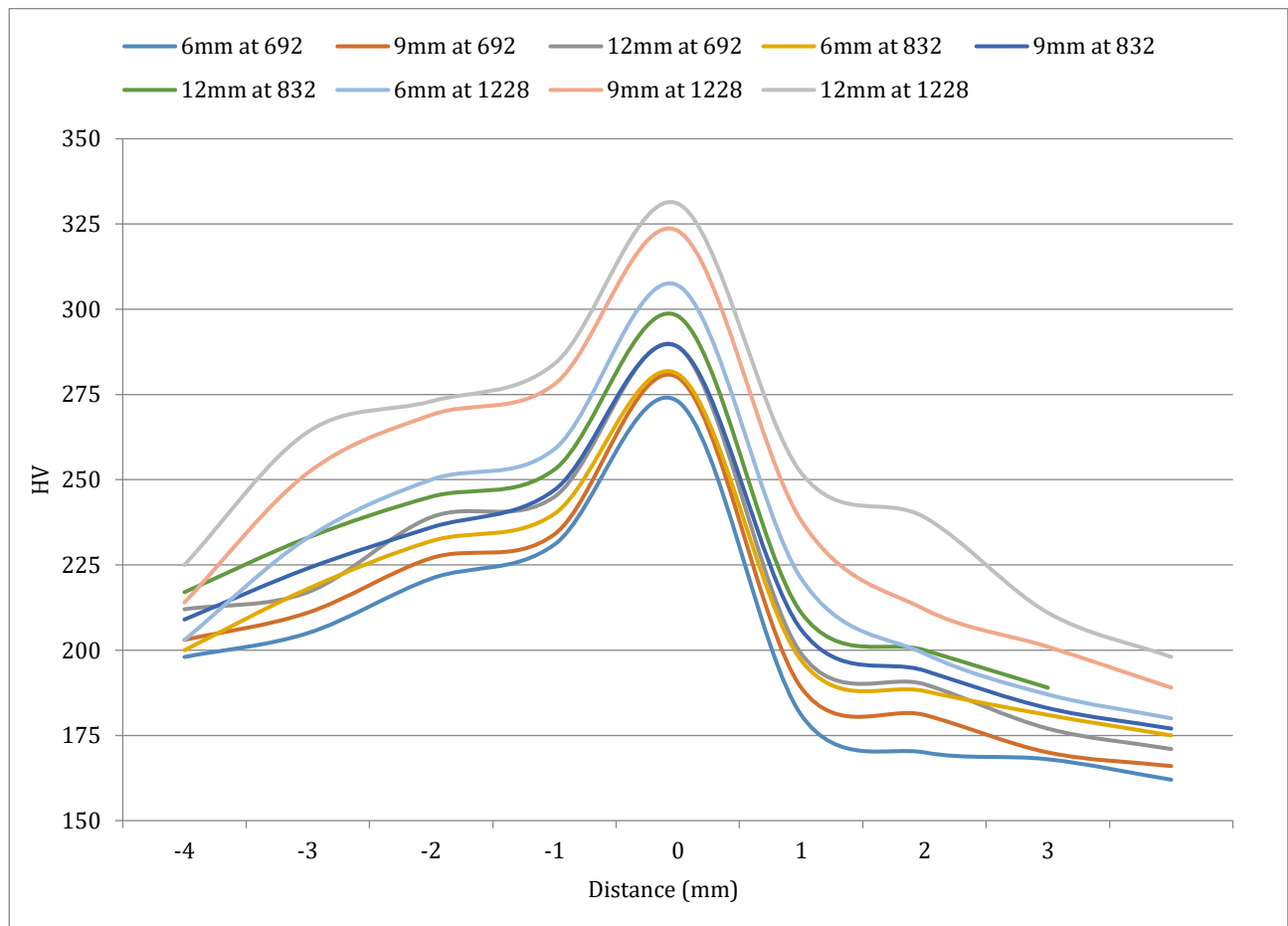


Fig. 2. Vickers micro-hardness for all sets.

3.3 Scanning Electron Microscopy and EDS Analysis

The JEOL model JSM-6610LV Scanning Electron Microscope (SEM) coupled with Energy

Dispersive Spectroscopy (EDS) was employed to analyze the fractured surfaces of tensile test specimens representing samples with varying tensile strengths. Magnified images were captured at 800X magnification at the fracture

sites of both SS304 and SS316 materials. The investigation focused on the correlation between tensile strength results and the visual characteristics observed on the fractured surfaces. In Fig. 3, the SEM analysis of the sample exhibiting the lowest tensile strength reveals a pure brittle failure mode, characterized by a lack of voids and dimples on the fractured surface. EDS data further confirms this observation, showing an enrichment of carbon (C), chromium (Cr), nickel (Ni), and iron (Fe) on the fractured surface of the weld joint. The high concentration of carbon at the weld suggests the formation of carbide-based compounds in significant quantities, alongside Cr, Ni, Fe, and other elements, likely contributing to the brittle fracture behavior. Figs. 4 and 5 depict SEM and EDS data for samples with moderate and highest tensile strengths, respectively. Despite the presence of a small number of dimples, indicative of a slight improvement in ductility, both samples still exhibit brittle failure behavior. The river

wave-like pattern observed suggests the presence of brittleness in the joint. Similar to the sample with the lowest tensile strength, an enrichment of C, Cr, Ni, and Fe is evident at the weld interface, leading to carbide formations. The presence of Chromium Carbides and Nickel Carbides, in combination with the Heat Affected Zone (HAZ), appears to have influenced the hardness value of the weld, contributing to its brittle fracture behavior. [8].

Furthermore, the micro-hardness value at the weld interface appears elevated, potentially attributed to the formation of brittle inter-metallic layers [9]. Tensile testing revealed a notably small duration before specimen failure. The presence of phosphorus was also noted, adversely affecting weld joint properties by inducing brittleness [10]. Increased phosphorus content in the material correlates with heightened hardness and brittleness [11].

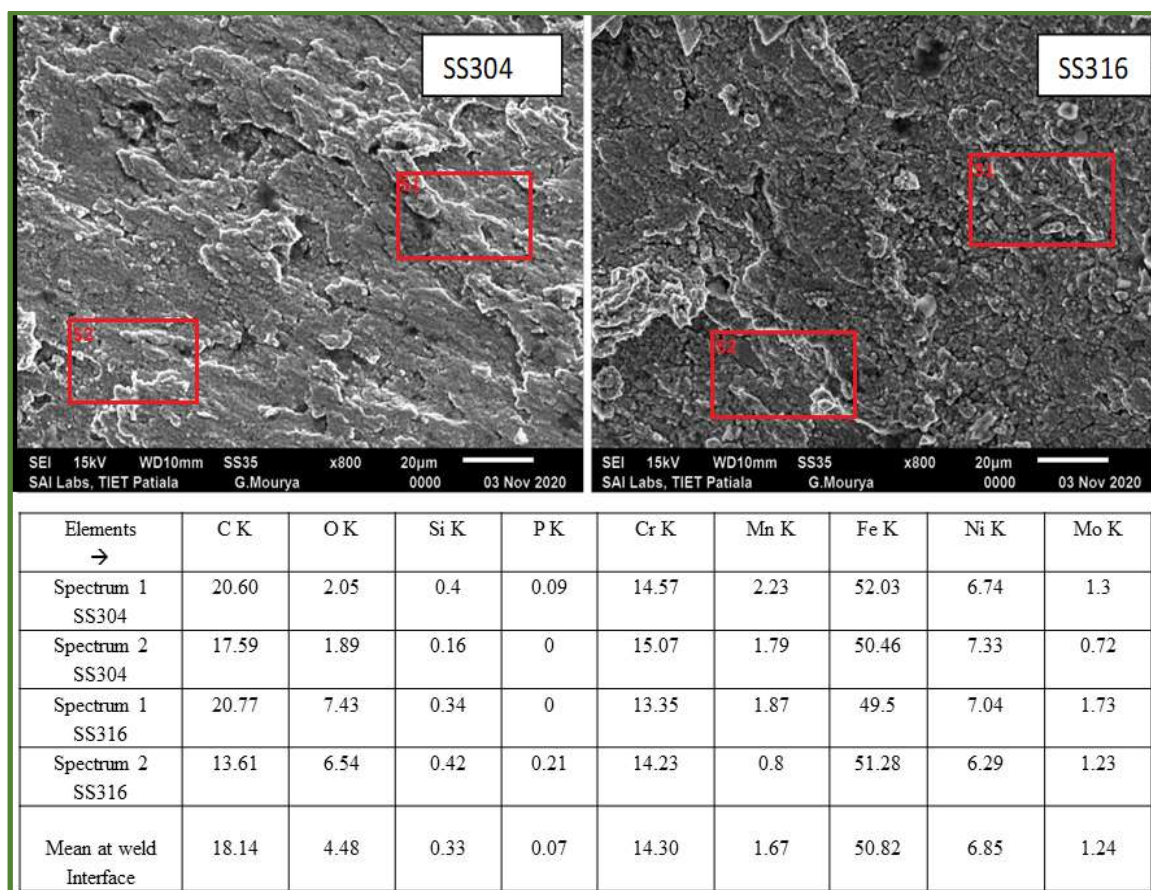


Fig. 3. SEM image and EDS data of lowest tensile strength sample.

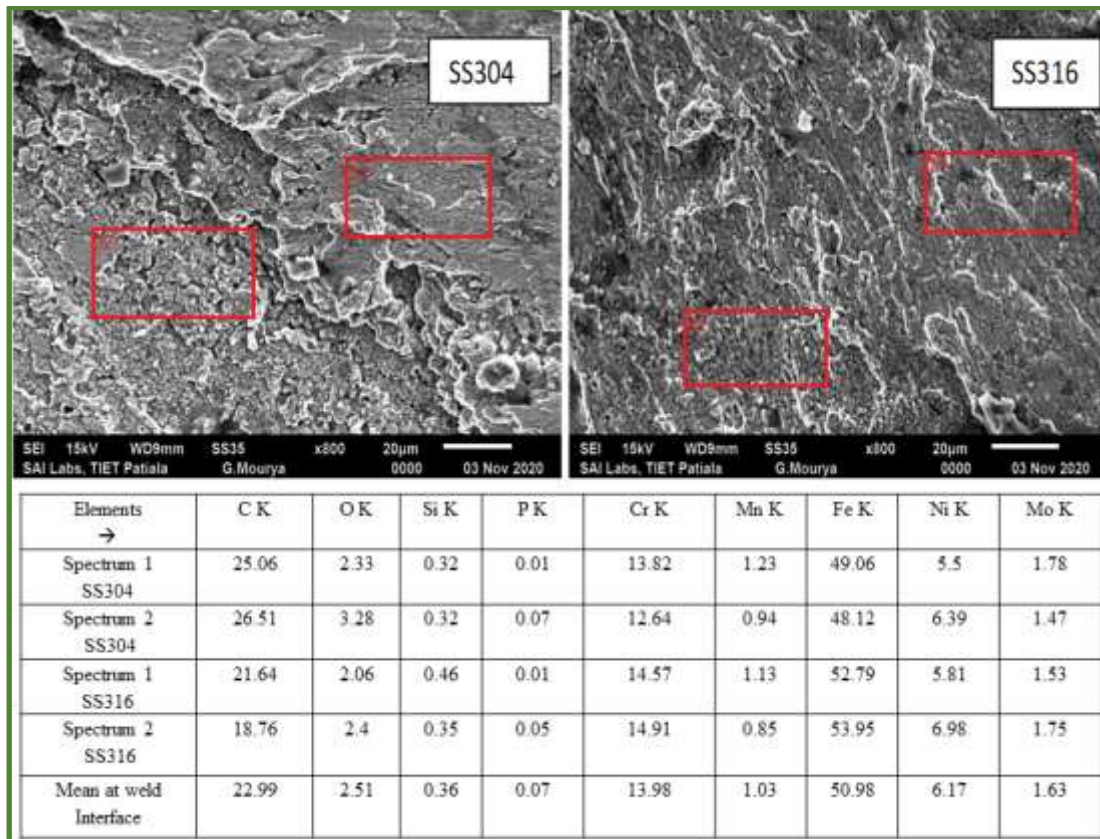


Fig. 4. SEM image and EDS data of moderate tensile strength sample.

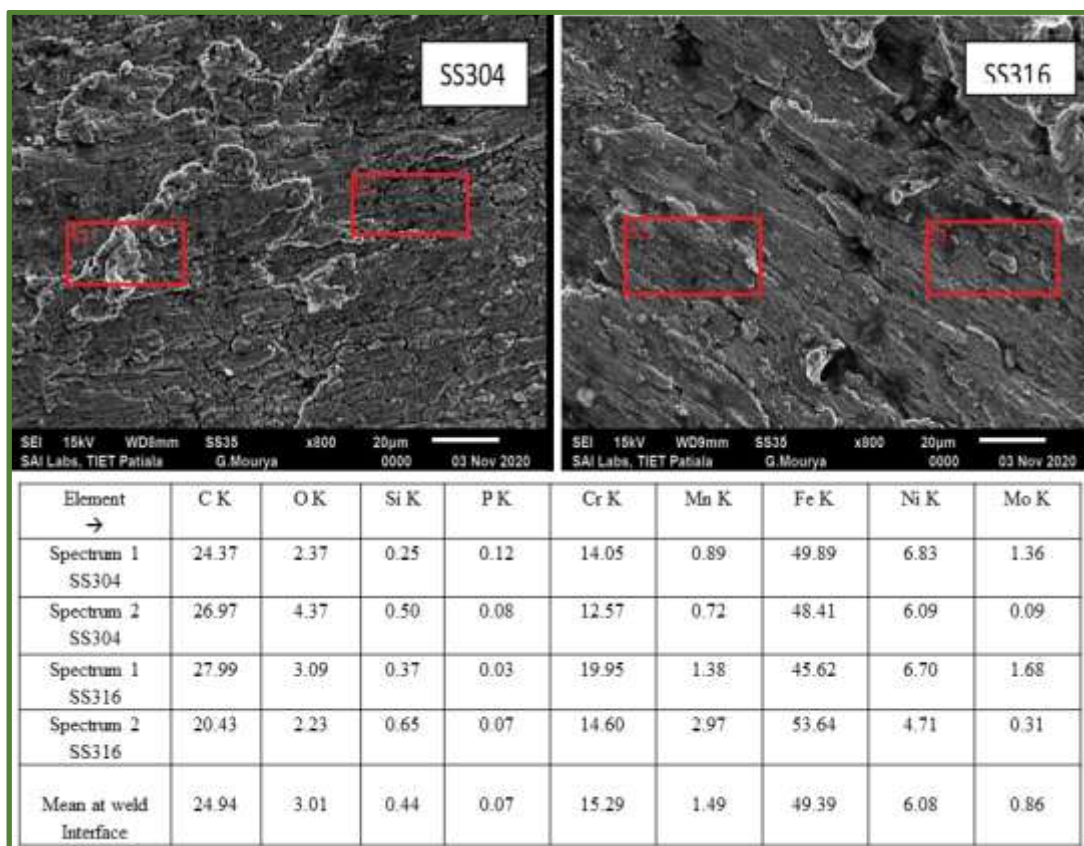


Fig. 5. SEM image and EDS data of highest tensile strength sample.

3.4 Optimizations of Parameters on the basis of Tensile

Signal to Noise analysis test is used to identify the significance and optimizations of process parameters. Minitab software is used to transform data shown in Table 2 into signal to noise ratio (S/N). Higher the Better (HB) or the Larger the Better (LTB) equation were used in this calculation [12]. The responses for signal to noise ratios are shown in Table 4 and plotted in Fig. 6. The most influencing parameter for as weld condition is burn-off length followed by rotational speed and forge time which was also noted in test results. The optimized set of

parameters for highest tensile stress value for as weld condition is rotational speed 1228 rpm and burn-off length 12 mm. Forges time remains insignificant in range.

Table 4. Response for Signal to Noise Ratios for tensile.

Level	Rotational Speed	Burn-off length	Forge Time
1	49.70	48.48	50.50
2	50.56	50.45	50.55
3	51.26	52.59	50.47
Delta	1.56	4.11	0.08
Rank	2	1	3

Larger is Better

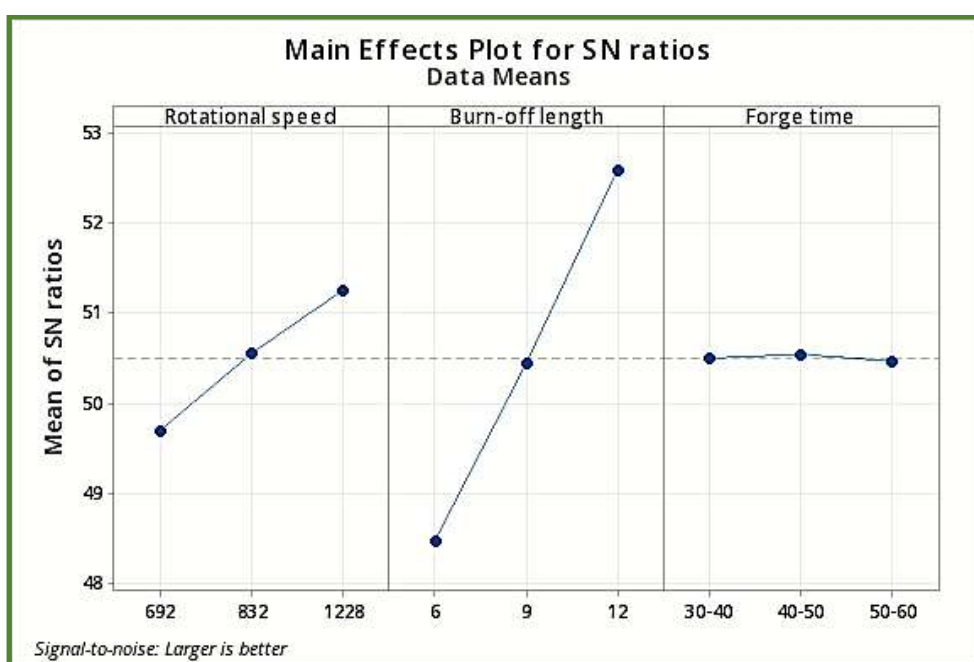


Fig. 6. Main Effects plot for Signal to Noise Ratios for tensile.

4. CONCLUSION

Based on the mechanical and micro-structural observations obtained from the present study on rotary friction welded joints between SS304 and SS316, the following conclusions are drawn:

- The maximum tensile strength value of 456.58 MPa was observed at parametric combination of 1228 rpm spindle speed, 12 mm burn-off length and 40-50 seconds forge time. It is perceived that the rotation speed and burn-off length also effect stress as the highest rotation speed and burn-off length has highest level of stress. This might be attributed that with the increase in rotational

speed and burn-off length, more mass was thought to be transferred at the interfaces.

- The peak hardness of 331 HV coincided with the conditions that yielded the highest stress levels, likely due to the elevated temperature generated at the contact surfaces.
- SEM images and EDS data observed at the weld interface of the fractured tensile samples depict brittle fractures. The higher presence of Chromium, Nickel, Phosphorus and Carbon leads to carbide formations which makes weld joint harder and brittle.
- Signal to Noise analysis test shows that the most influencing parameter is burn-off length followed by rotational speed and forges time remains insignificant.

- Materials with very high hardness can generate vibration problem during rotary friction welding process.

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