Analysis of Sensitization in Austenitic Stainless Steel-Welded Joint

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Abstract The main aim of this paper is to study the mechanical properties of the weld also the microstructure of the weld joints were analyzed. The effects of sensitization of gas tungsten arc (GTA) welded 304L stainless steel (SS) joints were observed. 304L stainless steel was heated to 450–950 °C, soaked for 0.5–2 h, and was observed. The three heat groups were chosen from the operative window of tungsten inert gas welding; these heat groups are low heat -2200 J/mm, medium heat–3320 J/mm, and high heat 3800 J/mm. Using these heat groups, weld joints were made which were normalized at 750 °C, 850 °C, and 1000 °C for 0.5 h, 1 h, and 2 h, respectively. These specimens were used to perform tensile test, impact strength test, microstructure, and microhardness for welded joint. The effect of sensitization was observed for these joints for stated mechanical properties. The outcomes of this study indicate that the tensile strength is maximum at weld joints normalized at 750 °C but remarkably decreased as the temperature was increased while the yield strength did not notably change with increasing of the temperature. The Charpy impact energy and micro-harness showed higher value at weld joints normalized at 750 °C but remarkably decreased as the temperature was increased. The major reason for Charpy impact energy decrease was compound of manganese–silicon–Sulfur formed in the weld pool during solidification. The microstructures of sensitized samples have been observed by optical microscope. The sensitization was found to be more for heat-treated welded joints and parent metal as compared to unprocessed weld joints and parent metal. Precisely, welded joints were normalized at 850 °C with soaking time 2 h and allowed to cool in a furnace was observed to be more sensitized.

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1 Introduction

Austenitic stainless steel has excellent corrosion resistance as well as mechanical properties but when the temperature is raised between 450 and 950 °C, the chromium rich carbides ($M_{23}C_6$) are formed near the grain boundaries which result in the corrosion. The chromium-depleted zone is formed near to the carbides. In this zone, the chromium concentration decreases to 12 wt% [1]. Austenitic stainless steel is sensitized when it is heat treated (normalized) in between 450 °C to 900 °C and soaked for 0.5–2 h. Sensitization reduces the chromium rich carbides which results improving corrosion resistance. With the diminution of chromium from chromium-enriched carbide at temperature between 450 and 950 °C encounters by the steel, in the Heat Affected Zone of a weld normally, Cr-enriched Cr carbide, M represents Cr and some minute quantity of Fe in $M_{23}C_6$. The carbon atom diffuses to grain boundaries where carbon atom combines with chromium atom to form chromium carbide at sensitization temperature. The chromium carbide precipitates from areas contiguous to the grain boundaries which result in depletion of chromium. These areas are anodic as compared to the rest of the grains and therefore results in intergranular corrosion, which are favorably attacked by corrosive media [2].

Sensitization results in dilapidation of corrosion resistance over and above the mechanical properties [3, 4]. Many researchers have analyzed the welding of austenitic stainless steel with the gas tungsten arc welding process and the mechanical properties of austenitic stainless steel [5–9] The welding techniques used and the sensitization situations are changed in every case. The mechanical properties and consequence of microstructure of welded 316L joints were studied by [10]. The best results were observed when the weld joint was prepared using shielded metal arc welding (SMAW). For preparing the weld joint, E316L-16 electrode was used at low heat input conditions along with 5% of ferrite.

2 Experimental Details

2.1 Base and Filler Material

For the present study, the base material used was AISI 304L austenitic stainless steel. Nine plates were formed of 25 cm (length) × 10 cm (width) × 0.6 cm (thickness). These samples were used for the gas tungsten arc welding and the filler material used was 304L stainless steel solid electrode of 0.315 cm diameter. The chemical composition of the material used for the experimentation is shown in Table 1.

Table 1 Composition of 304 L and the filler wire (in wt%)

Composition	Carbon	Manganese	Silicon	Chromium	Nickel	Phosphorus	Sulfur	Molybdenum
Base material (304L)	0.021	1.05	0.55	18.10	9.10	–	–	–
Filler wire (304L)	0.045	1.50	1.00	20.00	9.00	0.04	0.03	0.75

Table 2 Welding parameters used for butt welded joints

Welding current (A)	Voltage (V)	Pass	Welding velocity (mm/min)	Heat input (J/mm)	Total heat input (J/mm)
130	23	1st	98	1430	3320
		2nd	75	1890	
180	23	1st	105	1700	3800
		2nd	85	2100	
210	25	1st	215	1020	2200
		2nd	187	1180	

2.2 Welding Procedure

For the preparation of the specimen to be analyzed, the parent metal was cleaned with the 1500 grit sand paper. The contaminated particles like rust were removed from the parent metal before the welding process which will avoid the defects during welding. After cleaning the parent metal plate, it was held so as to perform the welding [11]. For the different heat input values, the current was changed from 130A to 210A at the constant voltage of 25 V along with the varying welding speed while preparing specimen.

There were no welding defects like blow holes and porosity while preparing the weld bead and also the weld geometry was good. The parameters selected for welding are given in Table 2. For the analysis of mechanical properties and the microstructure, the measurements were occupied from the section which is transverse to direction of flow of weld bead. The analysis of microstructures was detected with an optical microscope. Figure 1 shows the weld samples taken for the tests.

2.3 Sensitization Treatment

The welded samples were prepared at low heat input 2.2 kJ/mm (210A). The performances of these welds were found to be the best when compared to the welds with different heat input conditions for various mechanical properties like microhardness, tensile and impact strength, and microstructure. Therefore, 210 A current was chosen for the said analysis. Another test sample was prepared of SS 304 L which was 250 mm long, 500 mm wide, and 6 mm thick. The same procedure was followed and the same parameters were used as mentioned for last study. The nine samples were made from the welded plate and were normalized at different temperatures and different time of soaking. After that, various properties were examined for the prepared samples. The temperatures used for sensitization were 750, 850 and 1000 °C and the soaking time was 30, 60, and 120 min. Six different time and temperature conditions were selected for sensitization of samples.

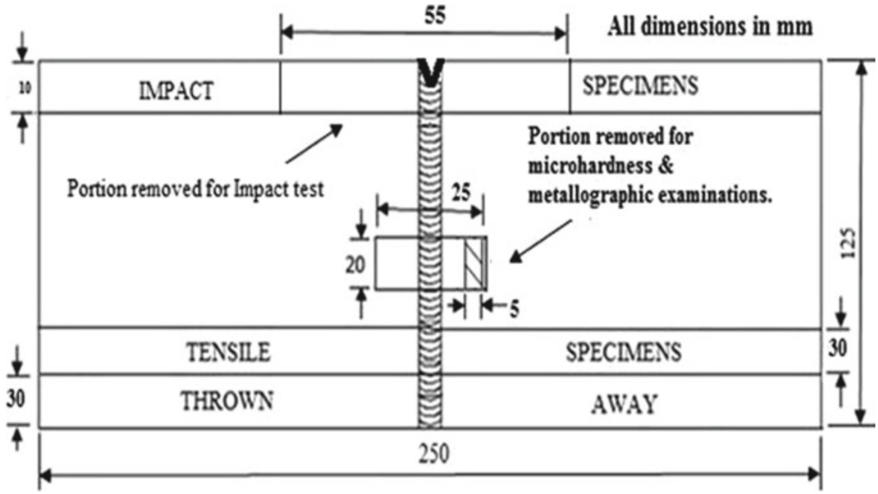

Fig. 1 Pattern of samples prepared from the welded plate

Heat treatment was done in muffle furnace. The nine specimens prepared from welded plate at 210 A were normalized and air cooled at above-stated temperature and time. For these samples, tensile strength, impact strength, microstructure, and microhardness were analyzed [12]. For example, three specimens were prepared at 750 °C with soaking time of 30 min and air cooled, and out of these three samples, one sample is used for tensile strength, second for impact strength, and third for microstructure and microhardness. Similarly, the next three samples were heated at 750 °C with soaking time of 60 min and air cooled. In the same way, all the specimens were prepared and the same properties were analyzed for these specimens.

2.4 Sampling of Specimen

Figure 1 shows the schematic diagram of the specimens prepared from the welded plate and their mechanical properties like tensile strength, impact strength, hardness, and microstructure were analyzed.

2.5 Tensile, Microhardness, and Impact Test

The weld pad was machined to prepare three specimens as shown in Fig. 2. The specimen prepared for analysis of tensile test, impact strength, and microhardness was taken according to ASTM E08 standards [9] as shown in Fig. 2. To perform the test on the various specimens, the hydraulically operated digital tensile test machine

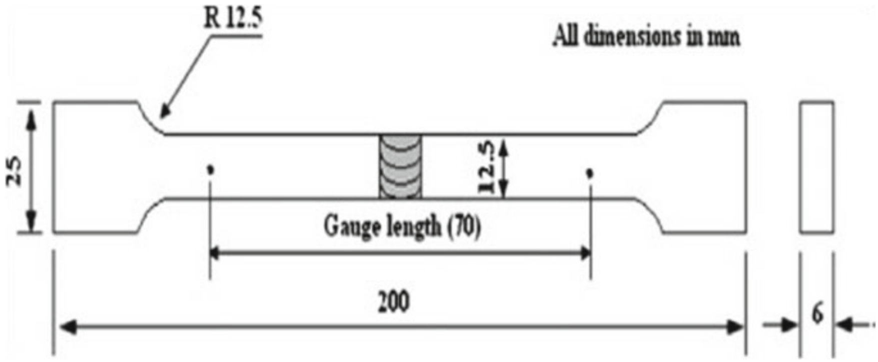

Fig. 2 Tensile specimen specifications

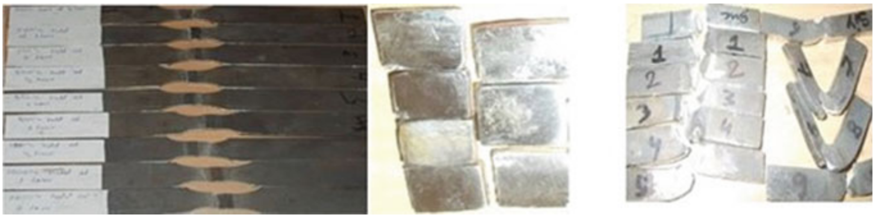

Fig. 3 Tensile-, microhardness-, and impact-tested specimens viewing the place of fracture at different normalization temperature

was used of capacity 400 kN. The Vickers's microhardness testing machine was used to check the microhardness. The load capacity of the machine is 0.5 kg. Impact strength was measured using Charpy impact testing machine. Figure 3 shows the photograph of the specimens after performing the above-mentioned tests [13–17].

2.6 Metallographic

The weld pad was machined to prepare the specimen as shown in Fig. 1. These specimens were analyzed for the change in microstructure of welding. The specimens were ground and cleaned with different grades of emery paper (800, 1000, 1500, and 2000 grit). Subsequent to cleaning the example with emery papers, every one of the examples was cleaned with velvet fabric utilizing alumina slurry. The last cleaning of the example was finished by precious stone glue (1 μm) utilizing Hiffin chloride as ointment. These cleaned examples were profound carved with Kalling's reagent (5 g copper (II) chloride, 100 ml hydrochloric acid and 100 ml ethanol) [10]. These specimens were finally observed using optical microscope.

3 Results and Discussion

3.1 Metallographic Studies of Specimen Welded at Different Welding Conditions

The micrographs of the specimen were analyzed and the presence of delta ferrite was observed in the matrix of austenite. Whereas the equiaxed grains of austenite are present in the parent metal. The dark bands observed are stringers of ferrite. These ferrite bands are least in weld at minimum heat input of 2.20 kJ/mm. The photomicrographs of the specimen are shown in Fig. 4. The currents selected for preparing specimen weld (130, 180, and 210 A) were cracked inside the weld bead. The strength of all the joints observed was good. When the specimen was polished, the lack of fusion was found which was prepared at 130 A. The tensile strength of 94.28% of the base metal was observed at low heat input of 2.2 kJ/mm. This tensile strength is the highest at given heat input. Hardness is maximum at 220 A and minimum because of arc formed by weak current at 130 A in the sample. Table 3 shows the macrostructural and microstructural details of the weld joints.

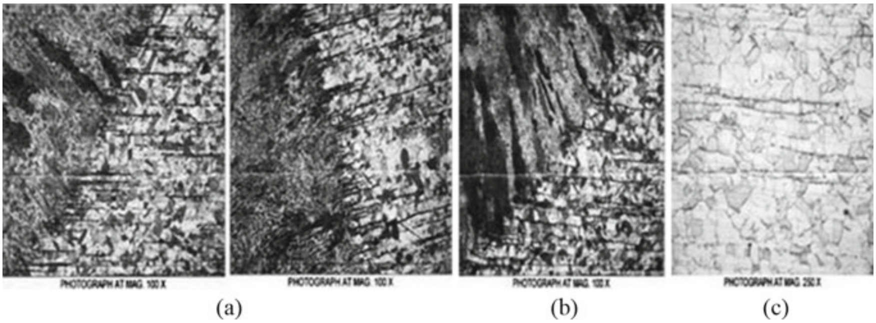

Fig. 4 Photographs of base material and welded joints at different heat inputs **a** 2.2 (kJ/mm), **b** 3.32 (kJ/mm), **c** 3.8 (kJ/mm), and **d** Base metal (at 100x)

Table 3 Mechanical properties details of the weld joints

Depiction	Tensile strength (GPa)	Yield strength (GPa)	Microhardness (HV)	Impact strength (J/mm^2)
Base material	0.7874	0.4535	253	1600
2200 (J/mm) (210A)	0.7477	0.2884	250	1560
3800 (J/mm) (180A)	0.4716	0.3049	250	1480
3320 (J/mm) (130A)	0.6300	0.2964	240	1400

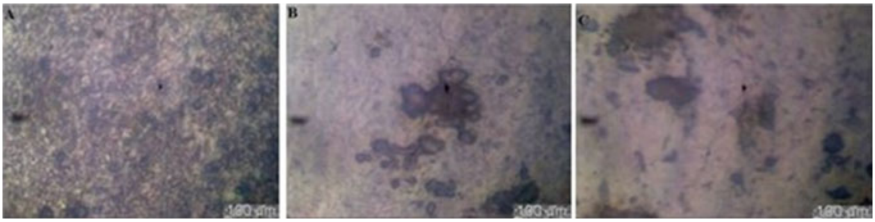

Fig. 5 **a** Optical micrograph showing the microstructure of sample heated to 750 °C held for 30 min, **b** Sample heated to 750 °C held for 1 h, **c** Sample heated to 750 °C held for 2 h

Table 4 Mechanical properties details of the weld joints normalizing at 750 °C

Description	Tensile strength (GPa)	Yield strength (GPa)	Microhardness (HV)	Impact strength (J/mm^2)
750 °C for 30 min	0.7507	0.4434	246	1400
750 °C for 1 h	0.7367	0.4770	235	1280
750 °C for 2 h	0.7321	0.4971	232	1200

3.2 Metallographic Studies of Specimen Normalizing at 750 °C

Figure 5 shows the photomicrographs of the specimen which were normalized at a temperature of 750 °C with soaking time of 30 min, 1 h, and 2 h, respectively. While analyzing the samples, the chromium-depleted zones were observed. These zones are negligible for the specimen with soaking time of 30 min. These chromium-depleted zones increase with the increase in soaking time. Table 4 shows the macrostructural and microstructural details of the weld joints normalizing at 750 °C. With the increase in normalization temperature and soaking time, the tensile strength, impact strength, and micro hardness decrease.

3.3 Metallographic Studies of Specimen Normalizing at 850 °C

Figure 6 shows the photomicrographs of the specimen which were normalized at a temperature of 850 °C with soaking time of 30 min, 1 h, and 2 h, respectively. The chromium depleted zones were also observed in these specimens also. These zones also increase with increase in soaking time. When the comparison of mechanical properties was done for samples sensitized at 850 and 750 °C, it has been found that the two samples resemble with each other. With the increase in normalization temperature and soaking time, the tensile strength, impact strength, and microhardness

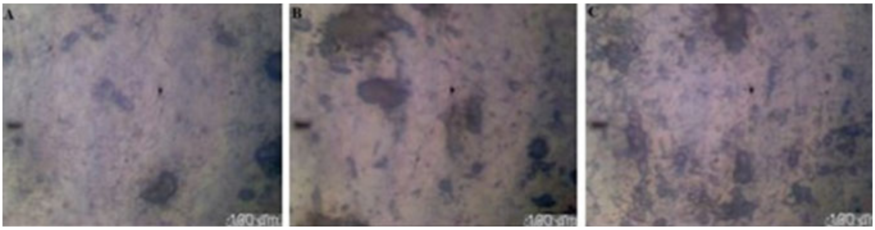

Fig. 6 **a** Optical micrograph showing the microstructure of sample heated to 850 °C held for 30 min, **b** Sample heated to 850 °C held for 1 h, and **c** Sample heated to 850 °C held for 2 h

Table 5 Mechanical properties details of the weld joints are normalizing at 850 °C

Description	Tensile strength (GPa)	Yield strength (GPa)	Microhardness (HV)	Impact strength (J/mm^2)
850 °C for 30 min	0.7426	0.4635	234	2600
850 °C for 1 h	0.7367	0.4526	260	2500
850 °C for 2 h	0.7220	0.4621	242	1900

decrease. Table 5 illustrates the mechanical properties of the weld joints which were normalized at 850 °C.

3.4 Metallographic Studies of Specimen Normalizing at 1000 °C

Figure 7 shows the photomicrographs of samples which were heat treated at 1000 °C. At high temperature, the carbide precipitates were observed which are negligible for sample whose soaking time is 30 min and minimum precipitates were observed for sample with soaking time 120 min. These precipitates are negligible with increase in temperature and expose time. Figure 7c clearly shows the desensitization. Table 6

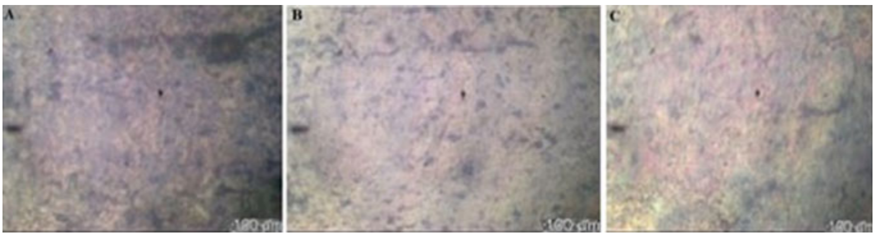

Fig. 7 **a** Optical micrograph showing the microstructure of sample heated to 1000 °C held for 30 min, **b** 1000 °C held for 1 h, and **c** 1000 °Cheld for 2 h

Table 6 Mechanical properties details of the weld joints normalizing at 1000 °C

Description	Tensile strength (GPa)	Yield strength (GPa)	Microhardness (HV)	Impact strength (J/mm^2)
1000 °C for 30 min	0.6168	0.4312	235	1.84
1000 °C for 1 h	0.6296	0.3765	227	2.00
1000°C for 2 h	0.6859	0.3710	225	2.20

shows the mechanical properties of weld. At 1000 °C, with soaking time 30 min, sensitization was observed for sample and desensitization was observed for sample with soaking time 1 h and 2 h. Tensile strength and impact strength were analyzed for 304L stainless steel which was normalized. The analysis shows that the tensile and impact strength increase with increase in temperature and time for soaking but the hardness decreases due to desensitization.

4 Conclusions

- The sensitization was observed for SS 304L when the samples were heated to a temperature of 750 and 850 °C with soaking time of 30, 60, and 120 min.
- The joint strength was observed to be good for all the three welds. But at minimum heat input 2200 (J/mm), the best result was observed. The microhardness and tensile strength of the sample are 250 HV and 0.7477 (GPa), respectively, as compared to 253 (HV) and 0.7874 (GPa) for the base metal.
- Tensile strength, impact strength, and hardness for 304L stainless steel decrease with increase in normalizing temperature and soaking time for the sample.
- At 1000 °C with soaking time 30 min, sensitization was observed for sample and desensitization was observed at 1 and 2 h soaking time.

References

1. Davis, J. R. (1994). *ASM specialty handbook*. ASM International: Stainless Steels.
2. Kumar, V., Arora, H., Pandey, P. K., & Rathore, V. (2015). Analysis of sensitization of austenitic stainless steel by different welding processes: a review. *International journal of applied engineering research, 17837–17848,* 10.
3. Wasnik, D. N., Kain, V., Samajdar, I., Verlinden, B., & De, P. K. (2002). Controlling grain boundary energy to make austenitic stainless steel resistance to intergranular stress corrosion cracking. *ASM Int., 402–407,* 12.
4. Unnikrishnan, R., Satish Idury K. S. N., Ismail, T. P., Bhadauria, A., Shekhawat, S. K., Khatirkar, R. K., & Sapate, S. G. (2014). Effect of heat input on the microstructure, residual stresses and corrosion resistance of 304L austenitic stainless steel weldments. *Material Characterization, 93*, 10–23.

5. Arora, H., Singh, R., & Brar, G. (2019). Thermal and structural modelling of arc welding processes: a literature review, *Measurement and Control.*
6. Prakash, C., Singh, S., Singh, M., Gupta, M. K., Mia, M., & Dhanda, A. (2019). Multi-objective parametric appraisal of pulsed current gas tungsten arc welding process by using hybrid optimization algorithms. *The International Journal of Advanced Manufacturing Technology*, *101*(1–4), 1107–1123.
7. Arora, H., Singh, R., & Brar, G. (2018). Finite element simulation of weld-induced residual stress in GTA welded thin cylinders. *Reference Module in Materials Science and Materials Engineering*, 1–14.
8. Atanda, P., Fatudimu, A., & Oluwole, O. (2010). Sensitization study of Normalized 316L Stainless Steel. *Journal Minerals and Materials Characterization and Engineering, 13–23,* 9.
9. Lo, K. H., Zeng, D., & Kwok, C. T. (2011). Effects of sensitisation-induced martensitic transformation on the tensile behaviour of 304 austenitic stainless steel. *Materials Science and Engineering A, 1003–1007,* 528.
10. Abigail Rodríguez, N., Packer, S., Steel, R., Rodrigo Muñiz, C., de Jesús Pérez, M., & Almanza, E. (2010). Analysis of sensitization phenomenon in friction stir welded 304 stainless steel. *Frontiers of Materials Science in China, 415–419,* 4.
11. Baek, J. H., Kim, Y. P., Kim, W. S., & Tai, Y. K. (2001). Fracture toughness And fatigue crack growth properties of the base metal and weld metal of a type 304 stainless steel pipeline for LNG transmission. *International Journal of Pressure Vessels and Piping, 351–357,* 78.
12. Prakash, C., Singh, S., Verma, K., Sidhu, S. S., & Singh, S. (2018). Synthesis and characterization of Mg-Zn-Mn-HA composite by spark plasma sintering process for orthopedic applications. *Vacuum, 155*, 578–584.
13. Prakash, C., Singh, S., Pruncu, C. I., Mishra, V., Królczyk, G., Pimenov, D. Y., & Pramanik, A. (2019). Surface modification of Ti-6Al-4V alloy by electrical discharge coating process using partially sintered Ti-Nb electrode. *Materials*, *12*(7), 1006.
14. Singh, S., Singh, G., Prakash, C., & Kumar, R. (2020). On the mechanical characteristics of friction stir welded dissimilar polymers: statistical analysis of the processing parameters and morphological investigations of the weld joint. *Journal of the Brazilian Society of Mechanical Sciences and Engineering, 42*(4), 1–12.
15. Singh, S., Prakash, C., & Gupta, M. K. (2020). On friction-stir welding of 3D printed thermoplastics. In *Materials Forming, Machining and Post Processing* (pp. 75–91). Cham: Springer.
16. Prakash, C., Singh, S., Singh, M., Gupta, M. K., Mia, M., & Dhanda, A. (2019). Multi-objective parametric appraisal of pulsed current gas tungsten arc welding process by using hybrid optimization algorithms. *The International Journal of Advanced Manufacturing Technology, 101*(1–4), 1107–1123.
17. Dhanda, A., Kansal, H. K., & Prakash, C. (2016). Experimental investigation and optimization of dissimilar joints of Aisi 304 and Aisi 4140 using pulsed current gas tungsten arc welding process. In *IVth International Conference on Production and Industrial Engineering (CPIE-2016)* (pp. 1–10). Jalandhar.