Indian Journal of Engineering & Materials Sciences
Vol. 25, June 2018, pp. 203-208

# Effect of induction heated friction stir welding on corrosive behaviour, mechanical properties and microstructure of AISI 410 stainless steel

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*Received 22 June 2017; accepted 29 August 2017*

In the current scenario, the industry requires a joining or welding method, which does not produce any environmental hazards. Friction stir welding (FSW) is the future of all metal joining methods because FSW does not produce any harmful byproducts and it enhances the joining strength too. The main limitation of friction stir welding was the difficulty to weld hard metals. The tool damage is very high while welding hard metals. These problems happen while using FSW can be recovered by using an additional heating source such as induction heating, arc heating or resistance heating. The induction heating is the quickest heating method as well as an economic method compared to other heating methods. AISI 410 stainless steel (SS) plate is difficult to weld by conventional welding methods, due to the glassy surface and this glassy surface cause sputtering. AISI 410 SS is chosen for this work and welded by using induction heated friction stir welding method (IH-FSW). The tool used for welding AISI 410 SS is made by using tungsten carbide with a hexagonal profile. A sound joint is fabricated at a spindle speed of 1200 rpm, welding speed of 45 mm/min, plunge depth of 0.05 mm and an additional heat input by using the induction-heating coil is about 100°C at 50 W power respectively.

**Keywords:** Induction heating, Stainless steel, Friction stir welding, Hybrid welding

After the invention of friction stir welding (FSW) in 1991, it is widely adopted in numerous industrial fields. While match up with conventional welding methods FSW process has huge advantages like solid state welding, shielding gas not required, high surface finish, less area of heat affected zone[1]. In the FSW process, the heat generated in the welding zone is achieved by the frictional heat produced by non-consumable tool and this welding is happening in the semisolid state. While employing FSW in hard metals and its alloys very high force is necessary to create friction between the tool and the work piece, this high force and high temperature generated in the frictional area causes tool damages like wear and cracking[2]. To avoid these troubles, a novel method is employed in this work called Induction Heated Friction Stir Welding (IH-FSW). A very new technique coined at the most recent time. This technique uses induction heat to in-situ heating in the localized welding zone. By implementing induction heating the metal become softened and it helps the FSW tool to move fast and the soften metal reduces the tool damage. The metal selected is AISI 410 stainless steel (SS). There is no resolidification related problems are arriving because the welding process is happening in semisolid state[3]. This IH-FSW is an eco friendly, energy efficient process because it does not produce any poisonous gases, and less energy is consumed for welding and heating.

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The well known application of AISI 410 SS is probably for cutlery and kitchenware[4,5]. The finest cutlery uses specially produced 410 for the knives, spoons and forks. The 410 can be hardened and tempered so that the knife blades will take a sharp edge[6]. The industries that use AISI 410 SS are the chemical, processing and oil and gas industries have created a large market for stainless tanks, pipes, pumps and valves as well. AISI 410 SS is used in desalination plants, sewage plants, offshore oilrigs, harbour supports and ships propellers. It is extensively used in the power generation industry to combat corrosion, particularly at elevated temperatures. In particular, AISI 410 SS is used for high temperature strength and oxidation resistance in fossil-fuelled power plants. The nuclear power industry also uses large quantities of AISI 410 SS, for both power generation and radiation containment. Special louvered ventilation shafts are made, which are designed to be used in emergencies to seal off plants for years if necessary. Steam and gas turbines use AISI 410 SS because of its corrosion resisting and heat resisting qualities[7]. Clean melted AISI 410 SS is used for medical implants and artificial hips. A great deal of medical equipment - such as orthopaedic beds, cabinets and examination machines - is made as standard from AISI 410 SS because of its hygienic and easy-clean qualities[8]. Cars are making increasing use of AISI 410 SS, primarily for exhaust systems and catalytic converters, but also for structural purposes. With greater attention being made to achieve lower long-term maintenance costs, less environmental impact and greater concern with life cycle costs.

## Experimental Procedure

### AISI 410 stainless steel (SS)

A hot rolled AISI 410 stainless steel (SS) of thickness 3 mm is selected for this work[9]. AISI 410 stainless steel is a ferrite stainless steel having ferromagnetic property. Induction heating is possible only in ferromagnetic steel. The basic chemical compositions of AISI 410 SS are Fe, <0.15% C, 11.5-13.5% Cr, >0.75% Ni, <1.0% Mn, <1.0% Si, <0.04% P, <0.03% S[10]. The physical properties of 410 SS are given Table 1 and the mechanical properties are in Table 2.

Stainless steel AISI 410 was machined to the required dimension of 200 mm length, 150 mm width and 3 mm thickness respectively. The joining faces carefully cut to make certain the edges are right angles. By using an HMT vertical milling machine, the experiments were conducted[11, 12]. The capacity of this milling is 7.5 HP; the maximum rotation speed is 1800 rpm and having a tool travel speed up to 135 mm/min. A moveable single-phase Induction heater using current 220V 50/60 Hz with the highest input current 20A is employed for in-situ heating the AISI 410 SS. In terms of wattage the induction heat input is given. With the aid of thermal imager, the amount of heat generated by the heating coil matching to the wattage rating is finding out. Figure 1 shows the working setup of induction assisted friction stir welding on AISI 410 SS.

### Friction stir welding tool

In soft metal welding by using FSW the circular threaded and tapered profiled tool pin gains sound joining. While employing such tool to hard metals the tool will be damaged easily and poor weld quality is shown[13]. The welding tool adopted for IH-FSW is tungsten carbide made, having pin length 2 mm, pin diameter 3 mm pin and have a shoulder diameter of 12 mm. The tool profile selected is hexagonal profile. Due to this hexagonal shape, the metal sitting in the nugget zone will be high[14]. The tool and its geometry are shown in Fig. 2.

### Induction heating coil

The induction-heating coil is made by using copper tube having outer diameter 2 mm. It has an inner diameter of 1.8 mm, through this coil. Cold water is continuously circulated while heating process to prevent overheating inside the induction heater. This coil has a diameter of 12 mm, shown in Fig. 3[15]. This coil helps localized pre heating of the metal in a volumetric way, where the tool is moving. The coil and tool shoulder have same diameter.

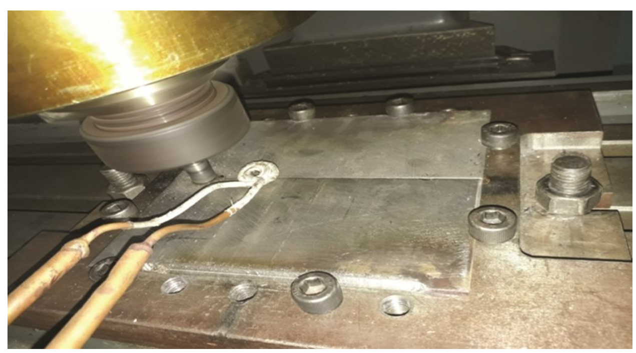

Fig. 1 — Induction assisted friction stir welding on AISI 410 SS

Table 1 — Physical properties of 410 SS

| Density ($kg/m^3$) | Elastic modulus (GPa) | Mean coefficient of thermal expansion (µm/m/°C) | | | Thermal conductivity (W/m.k) | | Specific heat (J/kg.K) | Electric resistivity (nΩ.m) |
|---|---|---|---|---|---|---|---|---|
| | | 0-100°C | 0-315$^0$C | 0-538°C | At 100°C | At 500°C | | |
| 7800 | 200 | 9.9 | 11 | 11.5 | 24.9 | 28.7 | 460 | 570 |

Table 2 — Mechanical properties of 410 SS

| Tensile strength (MPa) | Yield strength 0.2% proof (MPa) | Elongation at break (%) | Hardness, Vickers | Hardness, Rockwell C |
|---|---|---|---|---|
| 450 | 415 | 25 | 291 | 28.5 |

The outcome of four IH-FSW parameters on corrosive behaviour, mechanical properties and microstructure of AISI 410 SS joints are investigated. The four parameters are (a) spindle speed (1000, 1200 and 1400 rpm), (b) welding speed (30, 45 and 60 mm/min), (c) plunge depth (0.00 mm, 0.05 mm, 0.10 mm) and induction heat (50°C at 40 W, 100°C at 50 W, 150°C at 60 W). These parameters are selected after conducting trail experiments in different ranges.

***Corrosion testing***

The weight loss corrosion technique is employed to study the corrosion behaviour of the welded specimen. The specimen is cleaned and buffed manually before dipping into the solutions. The 1M HCL (92 mL distilled $H_2O$ + 8 mL HCL) and 0.5 M $H_2SO_4$ (96 mL distilled $H_2O$ + 4 mL $H_2SO_4$) solutions are taken for these tests. Each testing has been conducted for 24 h. The specimen having size 10 mm length, 10 mm width and 3 mm thickness respectively. It first took the weight of the cleaned specimen and then immersed in those two solutions for 24 h. The specimen was collected and cleaned again after completing 24 h[16]. Then the weights of the collected specimen are calculated. The rate of corrosion was found out by using corrosion rate formula.The specimen prepared for corrosion testing and after testing, was shown in Fig. 4.

**Tensile testing**

To investigate the mechanical behaviour of IH-FSW joints at different joining conditions, tensile specimens were machined out in the transverse direction so the weldment fits exactly in the middle[17]. Tensile testing was conducted according to the ASTM E8 - 04 standard at a strain rate of $1\times10^{-3}$ $s^{-1}$ (ref.[18]). Tensile samples before and after testing are shown in Fig. 5.

**Micro structure analysis**

The specimen is polished by drum polisher by using 200 to 1000 grade sanding sheet. Before dipping into the etchant solution, the specimen is buffed. Kalling's Number - 2, is the etchant solution taken for AISI 410 SS. This solution is prepared by blending $CuCl_2$ – 5 g, HCL – 100 mL, Ethanol – 100 mL, respectively[19]. The specimen dipped into the etchant solution having a temperature of 25°C for 10 s.

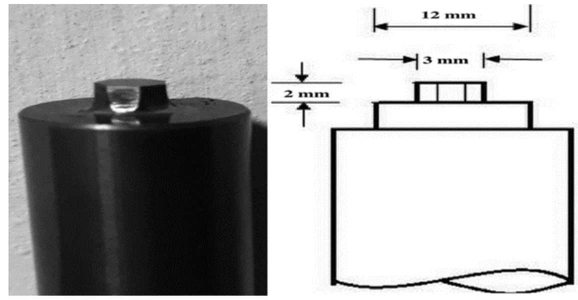


Fig. 2 — Tool and tool geometry


Fig. 3 — Induction heating coil having 12 mm diameter

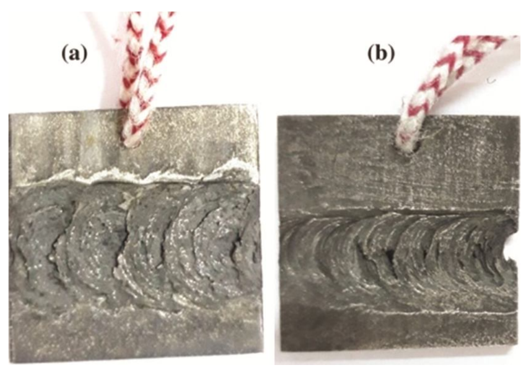


Fig. 4 — The specimen prepared (a) for corrosion test and (b) after corrosion testing

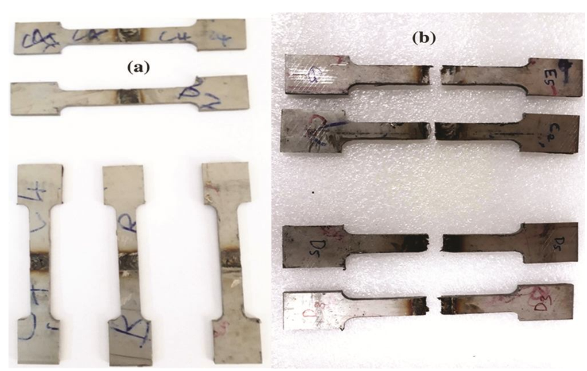


Fig. 5 — Tensile sample (a) before testing and (b) after testing

## Results and Discussion

### Corrosion test

The amount of material reduction in the weight loss method of corrosion test in 1 M HCL and 0.5 M $H_2SO_4$ for 24 h and the amount of corrosion was given in Table 3. The sample one is taken from the welded joint made of the parameters such as welding speed 30 mm/min, spindle speed 1000 rpm, plunge depth 0.0, induction heater input 40 W for 50°C. The sample two is taken from the welded joint made of the parameters such as welding speed 45 mm/min, spindle speed 1200 rpm, plunge depth 0.05, induction heater input 50 W for 100°C and the sample three is taken from the welded joint made of the parameters such as welding speed 60 mm/min, spindle speed 1400 rpm, plunge depth 0.1, induction heater input 60 W for 150°C[20-22]. The most influencing parameters for IH-FSW for AISI 410 SS are the spindle speed and the induction heat. The corrosion test proves that the additional heat does not make any change in the corrosion resistance property of AISI 410 SS until 100°C, the corrosion resistance property of the metal is gradually decreased by increasing in temperature. By using strong corrosion testing solutions proves that, this method of joining and this metal is applicable for all the marine as well as chemical industry applications.

$$Corrosion\ rate\ (CR) = \frac{(Weight\ loss\ (g) \times K)}{\left(\left(Alloy\ density\ \left(\frac{g}{cm^3}\right)\right) \times Exposed\ area(A) \times Exposure\ time(h)\right)}$$

*K* denotes the *K*-factor, it is a constant used for calculating the corrosion rate. For SI unit, the value of *K*- Factor is $8.75 \times 10^4$. The constant can be varied according to various units.

Sample calculation for Sample – 2

For 1 M HCL→Weight loss = 0.4247 g
*K* - Factor = $8.75 \times 10^4$
AISI 410 SS density = 7.80 g/cm$^3$
Exposed area = 100 cm$^2$
Exposure time = 24 h

Corrosion rate (CR) = $(0.4247 \times 8.75\times10^4) / (7.80 \times 100 \times 24) = 1.98511$

For 0.5 M $H_2SO_4$→ Weight loss = 0.6127g
*K* - Factor = $8.75 \times 10^4$
AISI 410 SS density = 7.80 g/cm$^3$
Exposed area = 100 cm$^2$
Exposure time = 24 hours

Corrosion rate (CR) = $(0.6127\times 8.75\times10^4) / (7.80 \times 100 \times 24) = 2.86385$.

Figures 6(a) and 6 (b) show the graphic representation of the corrosion rate for AISI 410 SS for solutions 1 M HCL and 0.5 M $H_2SO_4$, respectively. The best corrosion resistance was gained by the sample – 2.

### Mechanical properties

The ultimate tensile strength (UTS) of the welded samples was found out. The sample – 2 specimen gives the maximum strength, the parameters taken for joining the sample – 2 are, welding speed 45 mm/min, spindle speed 1200 rpm, plunge depth 0.05, induction heater input 50 W for 100°C. For this specimen the ultimate tensile strength gained was 456.43 N/mm$^2$.

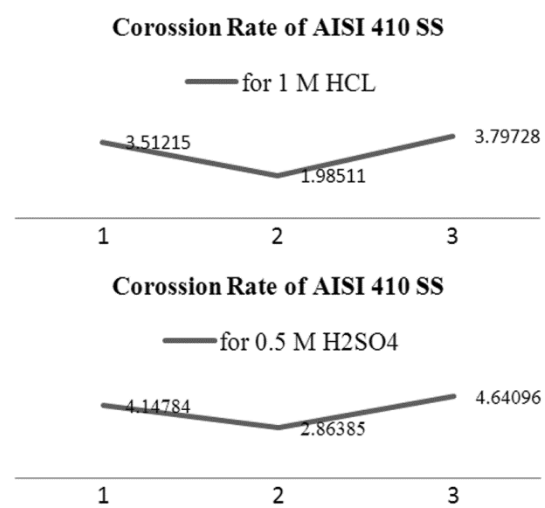


Fig. 6 — Corrosion rate for 1 M HCL and 0.5 M $H_2SO_4$

Table 3 — Weight lose in corrosion testing

| Corrosion testing | | Weight of the specimen before testing (g) | Weight of the specimen after testing (g) | Weight loss (g) | Corrosion rate (CR) |
|---|---|---|---|---|---|
| Sample – 1 | 1 M HCL | 14.0542 | 13.3028 | 0.7514 | 3.51215 |
| | 0.5 M $H_2SO_4$ | 14.3028 | 13.4154 | 0.8874 | 4.14784 |
| Sample – 2 | 1 M HCL | 14.9425 | 14.5178 | 0.4247 | 1.98511 |
| | 0.5 M $H_2SO_4$ | 14.7015 | 14.0888 | 0.6127 | 2.86385 |
| Sample – 3 | 1 M HCL | 14.0237 | 13.2113 | 0.8124 | 3.79728 |
| | 0.5 M $H_2SO_4$ | 14.1071 | 13.1142 | 0.9929 | 4.64096 |

The highest ultimate tensile strength given by the conventional arc welding is 324 $N/mm^2$ (ref.[23]), while comparing with arc welding process the tensile strength given by the IH-FSW is much higher and the production cost is low. In arc welding consumable filler rod is used, while in IH-FSW no consumable is used and this work is Eco friendly too, because IH-FSW does not produce any harmful gases or light rays. Figure 7 shows the UTS provided by the above three samples.

**Microstructure**

In Fig. 8(a), the grain structure and material flow in the welded region after welding are shown. The sample – 2 is selected for this. For this sample – 2 the induction heat given is 100°C at 50 W, this is the optimum heat input for the welding process. The other parameters for this sample – 2 are, rotation speed 1200 rpm, welding speed 45 mm/min, plunge depth 0.05 mm, respectively. The most predominant parameter for the IH-FSW for welding AISI 410 SS is spindle speed and the induction heat. The additional heat and the heat generated by the tool while welding does not make any change in the structure of the metal[24]. It also shows that the welding happens in solid sate itself. All through the joining process, the higher temperature is shown in the contact region of tool shoulder. A higher magnification picture of metal movement in the stir zone is shown in Fig. 8(b). This picture clearly shows the mixing of metals in the weld region. The pin's rotary movement results in fracturing and scattering in AISI 410 SS. At the weld nugget, wide spread grain refinement has been seemed[25]. Such microstructure was familiar at nugget zones and its occurrence was reported earlier. Higher magnified images of nugget zone are shown in Figs 8(c) and 8(d).

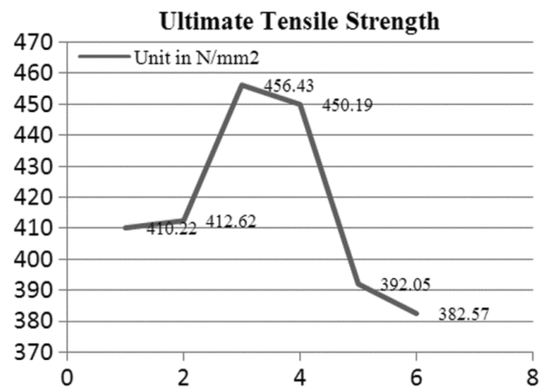


Fig 7 — The comparison of tensile strength of the test specimens

It has been found that the additional heat does not change the corrosion resistant property of AISI 410 SS. The additional heating enhances the welding speed and increases the tool life too. The tensile strength provided by the sample joint is pretty higher compared to the conventional welding methods. Welding quality was found to be poor at low induction heat inputs where poor plasticizing and mixing happens. While at very high induction heat inputs, sample joints show low mechanical properties

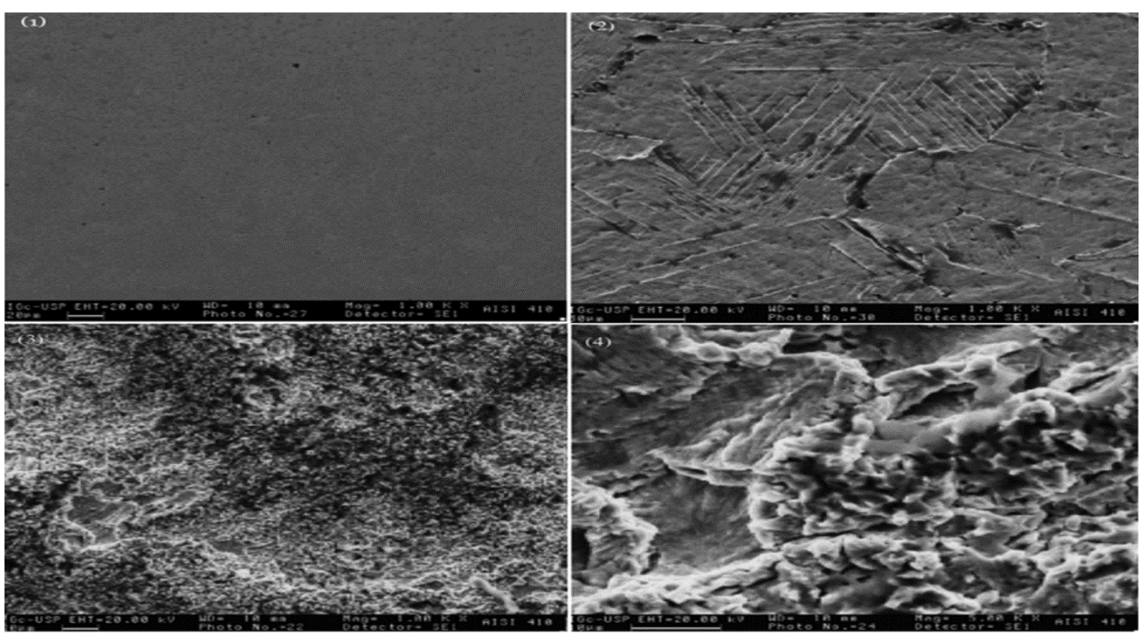

Fig. 8 — Optical microstructure of (a,b) the weld region and the stir zone of sample 2 and (c,d) the weld nugget zone

due to increase in the heat affected zone. The highest ultimate tensile strength gained was 456.43 N/mm$^2$ for the sample – 2. The sample – 2 shows less corrosive behaviour and good hardness while compared to the other samples. The corrosion property of the metal was reduced while increasing the temperature.

## Conclusions

Stainless steel AISI 410 was successfully welded by using induction heated friction stir welding method by using hexagonal tool pin profile. The following conclusions can be drawn from this study:

(i) The best parameter for welding AISI 410 SS is found out. The highest welding strength gained using the rotation speed 1200 rpm, welding speed 45 mm/min, plunge depth 0.05 mm and induction heat input 50 W for 100°C. The highest tensile strength gained was 456.43 N/mm$^2$ for the second test specimen. The tensile fracture was occurring on the retreating side due to the formation of coarse grains.

(ii) The corrosion tests show that the increase in the additional temperature above 100°C decreases the corrosion resistance property of the AISI 410 SS.

(iii) The microstructure shows that, the tool pin's rotary movement and the additional heat causes scattering and fracture in the weld nugget zone. These effects are reported earlier works too.

## Acknowledgement

The authors would like to acknowledge the funding for this project (No.: F/2016-17/NFO–2015–17–KER–393) from University Grants Commission (UGC) New Delhi

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