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Thermal Assisted Friction Stir Welding of HSLA Steel : A Novel Approach to Mitigate Lower Toughness and Ductility

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ABSTRACT

Friction stir welding (FSW) technology is well-known forits capability to join low softening metals and alloys such as aluminum and magnesium, conversely, high softening alloys like steel, titanium and nickel alloys is still a challenge due to tool material stringent property requirements and its availability. Presently, with the advancement in the development of tool materials,the joining of high softening alloysis possible. However, in case of high strength quench sensitive grade of steel, high cooling rate associated during FSW induces undesirable brittle martensitic microstructure and therefore, reduces the properties of the weld zone, particularly, the ductility and toughness. Therefore, in present investigation a novel approach to control the microstructure was investigated by employing induction pre heating source ahead of tool pin during FSW. The HSLA plate preheated at 300 °C and 600 °C respectively resulted in simultaneous increase of ductility and toughness because of widmanstätten ferrite and bainitic microstructure due to lower cooling rate. In case of FSW carried out without preheating the hard brittle zone was found, whereas the same was eliminated with preheating source. Optical and scanning electron microscope (SEM) with electron back scattered diffraction (EBSD) detector was utilized to characterize the microstructure of FSW nugget zone, and was correlated with mechanical properties.

Keywords: Thermal Assisted Friction Stir Welding; High Strength Low Alloy Steel (HSLA); Microstructure, Mechanical Properties; Scanning Electron Microscopy.

1.0 INTRODUCTION

The demand and market of naval pressure vessel is growing at a rapid pace and in order to meet the increased industrial and service requirements, more efficient designs and manufacturing conditions are being investigated. Particularly, the weight saving can be achieved by using higher strength steel and also by improving manufacturing condition by innovative and novel processes and design. The use of advanced high strength steel for the pressure vessel, hull and super structure is a solution which allows a significant weight saving by reduction of structure thicknesses. This approach can be implemented if the concomitant manufacturing process must be accordingly developed [1].

There are several limitations of fusion welding processes such as requirement of preheating, filler metal and inert gases and tools for minimizing the distortions. Moreover, welding defects like lack of fusion, inclusions, cold cracking, porosity and undercuts are commonly observed and requires reworks for repairing and finishing. On the other hand, the friction stir welding (FSW) is a solid state welding process developed by The Welding Institute UK without using filler metal addition during welding. This process is now being extensively used as an alternative welding process and thus, eliminates the disadvantages associated with the fusion welding process [2- 3]. Currently, the FSW method is well established process for welding of low softening metals like aluminum for civil, military and space applications, still there are many scientific and technological hurdles for high softening metal like steel, titanium and nickel. Researchers have demonstrated the importance associated with FSW such as the higher productivity, in-built mechanization, recrystallized grains with minimum heat affected zone, better mechanical properties and also avoidance of hydrogen induced crackingin case of high strength low alloy steel [3].

High strength low alloy steel (HSLA) is a class of steels which provides good combinations of strength, toughness, and weldability is commonly alloyed with nickel, chromium, manganese, molybdenum and copper and mostly used in the construction of offshore pipelines and ship constructions [4-5]. Many researchers reported possibility of FSW of HSLA steel with enhanced mechanical properties in particular strength and hardness, however, lower ductility and toughness still remains an area of concern [6]. This hard and brittle zone and lower toughness after FSW has been reported in various steels including HSLA steel [7-8].

In this investigation, the influence of thermal preheating and subsequently its effect on cooling rate after FSW was studied, with an aim to control and mitigate the formation of hard brittle zone in FSW HSLA steels. The effect of induction preheating on weld cooling rate on microstructure and properties of submarine grade HSLA steel (YS>700 MPa) was established with an objective to industrially make the process viable for fabrication of HSLA structures.

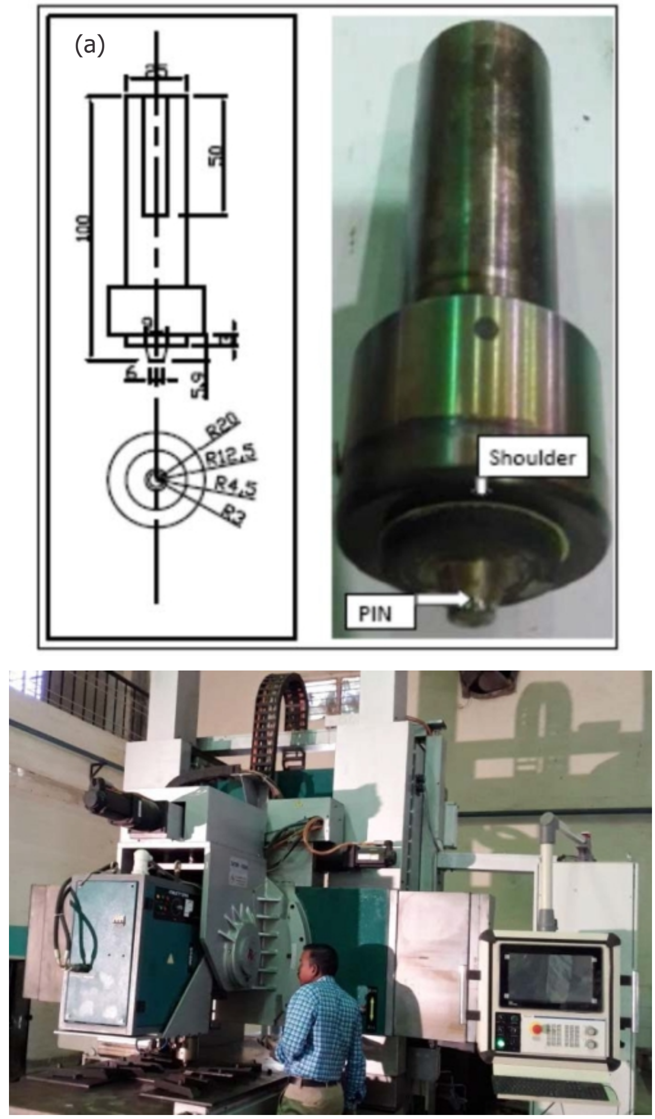

Fig.1 : Drawing and image of indigenously designed and developed (a) W-25Re tool used for FSW trials and (b) 100 kN thermal assisted FSW machine.

Table 1 : Chemical Composition of HSLA steel.

Elements	C	Si	Mn	P	S	Cr	Cu	Mo	V	Ni
% Max.	0.15	0.25	0.50	0.01	0.01	0.5	0.25	0.40	0.009	4.8

Table 2 : Mechanical Properties of HSLA Steel

Mechanical Properties	YS (MPa)	UTS (MPa)	% Elongation	Hardness (Hv)	YS/UTS	Charpy RT	Impact (J) -40 °C
HSLA Steel	710±10	890±16	22±4	270±14	0.79	217±3	204±5

2.0 EXPERIMENTAL DETAILS

(b)

HSLA steel (YS>700MPa) submarine grade steel plates of 6 mm thickness were used for friction stir welding. The chemistry and mechanical property of the steel is presented in **Table 1** and **Table 2**.

The room temperature FSW parameters were carried out using W-25Re tool having tapered cylindrical pin with 9 and 6 mm diameter and 5.9 mm length. **Fig. 1(a)** represents the features of W-25Re tool used in the experiment. All the experimental trails were carried out on indigenously design and developed 100 kN thermal assisted FSW machine as shown in **Fig. 1(b)**.

HSLA steel plate of size 250X100X6 mm were used using optimized process parameters i.e. spindle speed of 600 rpm with counter clockwise direction rotation and feed rate of 50 mm/min. Two experimental trials were carried out using induction coil of 10 kW and induction power was controlled so that, constant temperature of 300 °C and 600 °C were maintained during FSW. A hole was drilled at the center of plate so that K-type thermocouple could be placed closed to TMAZ region and the temperature profile is plotted to analyze the effect of preheating apart from Megastir® temperature telemetry system to measure the tool temperature. The trials were conducted at room temperature (RT), 300 and 600 °C are referred as FSW-HSLA-RT, FSW- HSLA-300 and FSW-HSLA-600 respectively **(Fig. 2 (a), (b) & (c))**. The induction coil (50 mm X 200 mm) was placed 5 mm over the base plate and once the desired pre heating temperature i.e. 300 & 600 °C was achieved, FSW welding was carried out keeping the induction preheating switched on throughout the length of the plate.

All the experimental FSW welded plates were examined by X-ray radiography as per ASTM 02B-11 to find the welding defects, if any, in the nugget zone.

3.0 RESULTS AND DISCUSSIONS

FSW is characterized by fast cooling due to lower temperature rise and rapid heat extraction by large FSW machine bed and also it is well established that the microstructure of the steel is dependent on the cooling rate. Therefore, the effect of induction preheating on cooling rate was studied using a thermocouple was placed at the TMAZ region. The temperature profile consists of peak temperature and post weld cooling of all the three experiments viz. FSW-HSLA-RT, FSW-HSLA-300 and FSW-HSLA-600 as shown in the **Fig. 3 (a)**, **(b)** and **(c)**. The cooling rate was calculated from the graph at temperatures between 800°C to 500°C (T800-500).

The cooling rate calculated from the graph was found to be 25 °C/sec, 8 °C/sec and 3 °C/sec for FSW-HSLA-RT, FSW-HSLA-300, and FSW-HSLA-600 respectively. Although keeping the FSW parameters same for all the experiments, changing the preheating temperature significantly changes the micro-structure. The microstructure characterization were carried out using optical and SEM with electron back scattered detector technique (EBSD) and reveals different morphologies of ferrite, bainitic with martensitic island and bainite with widmanstätten ferrite in FSW-HSLA-RT, FSW-HSLA-300, and FSW-HSLA-600 samples respectively as shown in the **Fig. 4** and **Fig. 5(a), (b), (c)**. The microstructure of the base metal is mainly characterized by equiaxed grains of tempered martensite, which get transformed to upper bainite with polygonal and GB ferrite. This transformation indicates that the material experienced a peak temperature in excess of A3 temperature even at lowest cooling rate. The prior austenite grain size as well as ferrite lathe size were measured and along with these features ferrite morphology such as grain boundary ferrite (α_{GB}), widmanstätten ferrite (α_W) and martensite is also marked in the **Fig. 4** for better clarity.

Fig. 2 : Photographs showing FSW welded plates carried out at (a) room temperature, (b) 300 °C and (c) 600 °C respectively.

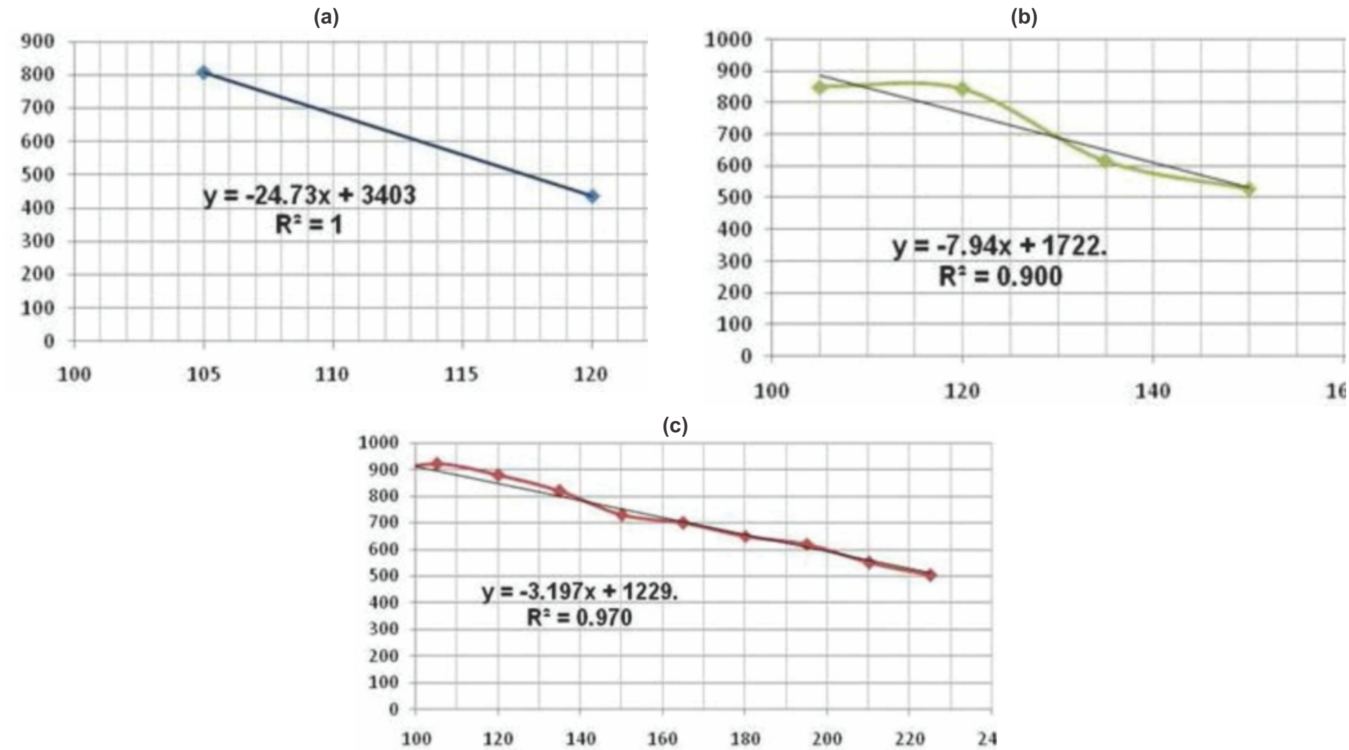

Fig 3. Effect of induction preheating on cooling rate of (a) FSW at RT (b) FSW at 300° (c) FSW at 600°C.

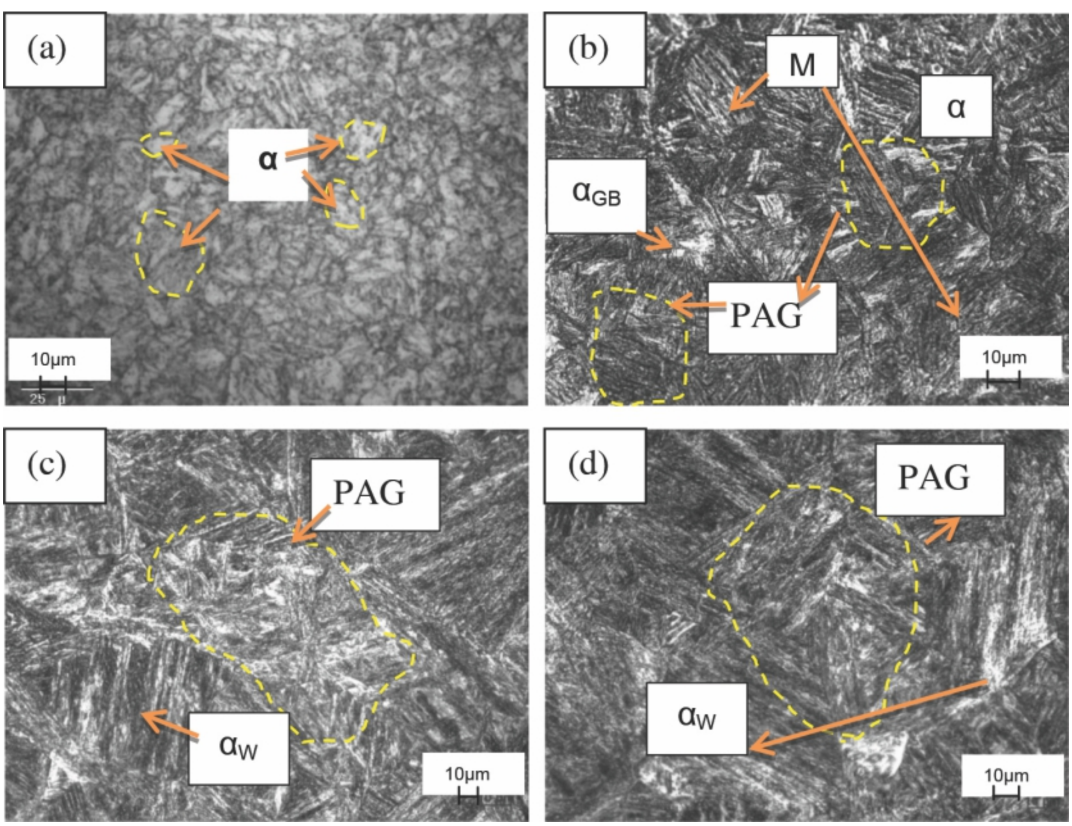

Fig. 4 : Optical images showing the effect of induction preheating on microstructure of stir zone of(a) FSW-HSLA-RT, (b) FSW-HSLA-300and (c) FSW-HSLA-600.

The ferrite lathe width is less than 2 µm in most cases, therefore, SEM and EBSD microstructure were taken to measure the ferrite lathe size and reveal the finer details of the microstructure. The ferrite lathe (width) size increases from 0.97 µm to 2.5 µm for the sample FSW-HSLA-RT (highest cooling rate i.e. 25 °C/sec) to FSW-HSLA-600 (lowest cooling rate i.e. 3 °C/sec). The prior austenite grain size, tempered martensite and ferrite lathe width measurement data is presented in **Table 3**. Also, with the variation in microstructure features, the hardness of the stir zone shows strong relationship with the ferrite lathe size. The finer the lathe size, the higher is the hardness; the hardness decreased from 460 Hv (RT) to 355 Hv (600) and similar results was also indicated by Nelson and Rose [6-7]. They also indicated that the hardness of the nugget zone increase significantly if the cooling rate is faster than 20 °C/sec and thereby resulted in presence of hard zone in the microstructure [7].

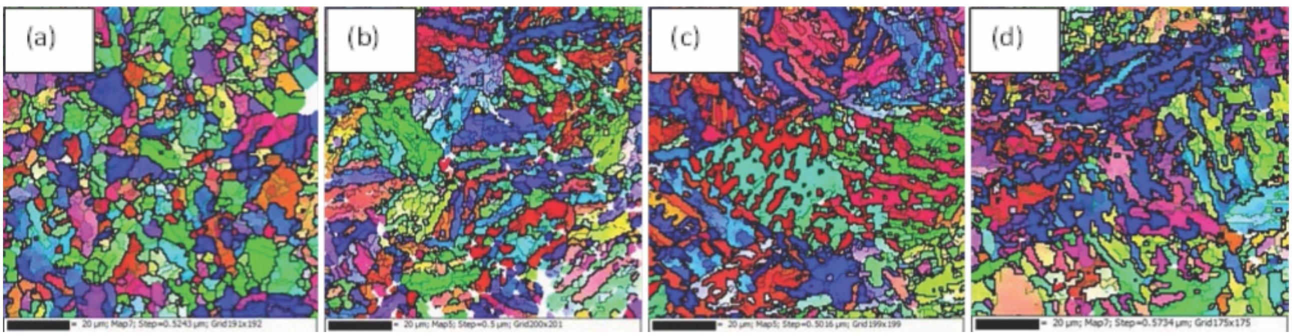

Fig. 5 : EBSD IPF images showing the effect of induction preheating on microstructure of stir zone of (a) FSW at RT, (b) FSW at 300°Cand (c) FSW at 600°C.

Table 3 : Variation in grain size and hardness

Nomenclature	Welding Parameters		Grain Size (µm)	Ferrite late Size (width) (µm)	Hardness (Hv)
	Spindle speed (rpm)	Travelling velocity (mm/min)			
Base Metal			16 (Tempered Martensite)	--	270±14
FSW-HSLA-RT	600	50	28±6 (PAG)	0.97±0.3	460±9
FSW-HSLA-300	600	50	40±9 (PAG)	1.75±0.58	367±8
FSW-HSLA-600	600	50	42±7 (PAG)	2.55±0.9	355±10

The relationship between the hardness of the various zone can be better realized by plotting hardness profile, the same is presented in **Fig. 6**. The macrostructure of the FSW zone along with the hardness of the respective zone is indicated with an arrow. The TMAZ zone is showing lower hardness as compared to the stir zone in all the samples. Furthermore, the value of the hardness of RT sample is displaying more hardness in the entire zone as compared to other samples (300 and 600) due to presence of martensite and finer ferrite lathe size as explained earlier.

The room temperature FSW tensile properties show near equivalent yield and ultimate tensile strength with lower ductility and toughness, the value is tabulated in the **Table 4**. However, for the samples with preheating source that is FSW-HSLA-300 and FSW-HSLA-600 indicates nearly 10% more yield and ultimate tensile strength with acceptable ductility and toughness. The toughness is very important property for structural ship building application and therefore, the lower toughness during FSW-HSLA-RT can be improved by use of thermal source. The improved strength and toughness is attributed by the presence if widmanstätten ferrite and upper bainitic microstructure and thus, hard martensite zone present in FSW-HSLA-RT can be mitigated.

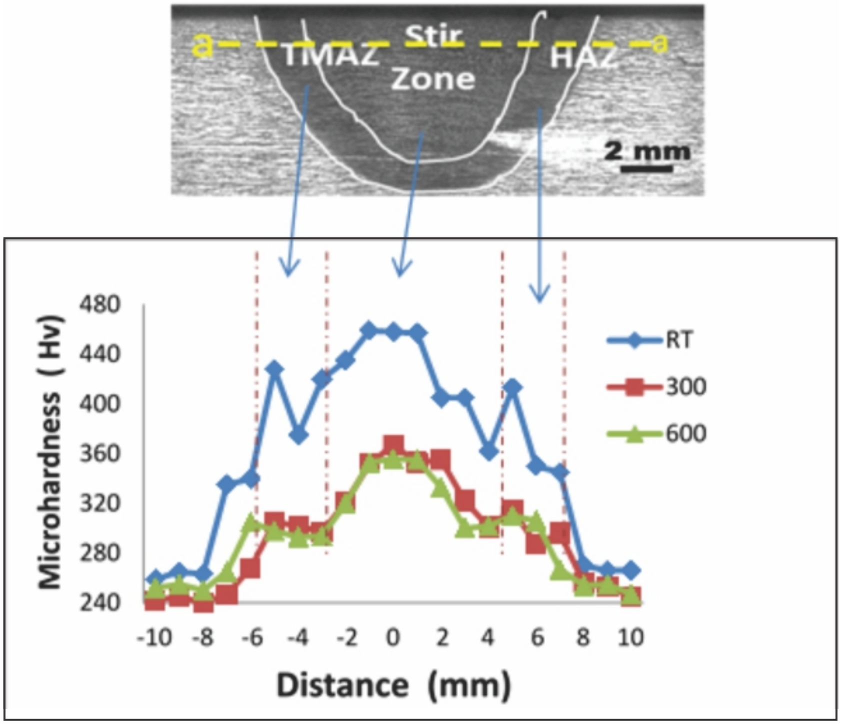

Fig. 6 : (a) Macrostructure of the of the stir zone (RT) and (b) hardness profile of the different zone of FSW-HSLA-RT, FSW-HSLA-300, and FSW-HSLA-600 sample.

Table 4 : Tensile properties of FSW-HSLA-RT, FSW-HSLA-300 and FSW-HSLA-600 samples.

Sr. No.	Nomenclature	Yield Strength (MPa)	UTS (MPa)	% Elongation	YS/UTS Ratio (%)	Fracture Location
1.	FSW-RT	645 ± 11	809 ± 9	17 ± 6	81 ± 2	In Base Metal
2.	FSW-300	708 ± 9	949 ± 8	15 ± 7	74 ± 2	In Base Metal
3.	FSW-600	711 ± 9	932 ± 12	16 ± 6	76 ± 3	In Base Metal

The charpy impact toughness of the base metal is 117 J and 104 J at room temperature and -40°C, the data is presented in **Table 5**. However, the impact strength of FSW-HSLA-RT sample exhibits 58 J, which is 50% lower than base metal; this is due to presence of small cluster of martensite in the microstructure. The fractography study also indicated quasi cleavage mixed mode fracture features and is in line with the charpy toughness result. The effect of preheating on toughness properties is clearly observed in FSW-HSLA-300 and FSW-HSLA-600 samples having 91 and 100 J toughness at room temperature. The fractrographs also indicate ductile dimples features in FSW-HSLA-300 and FSW-HSLA-600 samples, as shown in **Fig. 7**.

Table 5 : Charpy toughness properties of FSW-HSLA-RT, FSW-HSLA-300 and FSW-HSLA-600 samples (sub size 5 mm X 5 mm) .

Sl. No.	Nomenclature	Charpy Impact (J)	
		Roo Temp.	-40°C
1	BASE METAL	117±3	104±4
2	Without Preheating (RT)	58±4	52±5
3	Preheating at 300°C (300)	90±2	84±4
4	Preheating at 600°C (600)	100±3	88±4

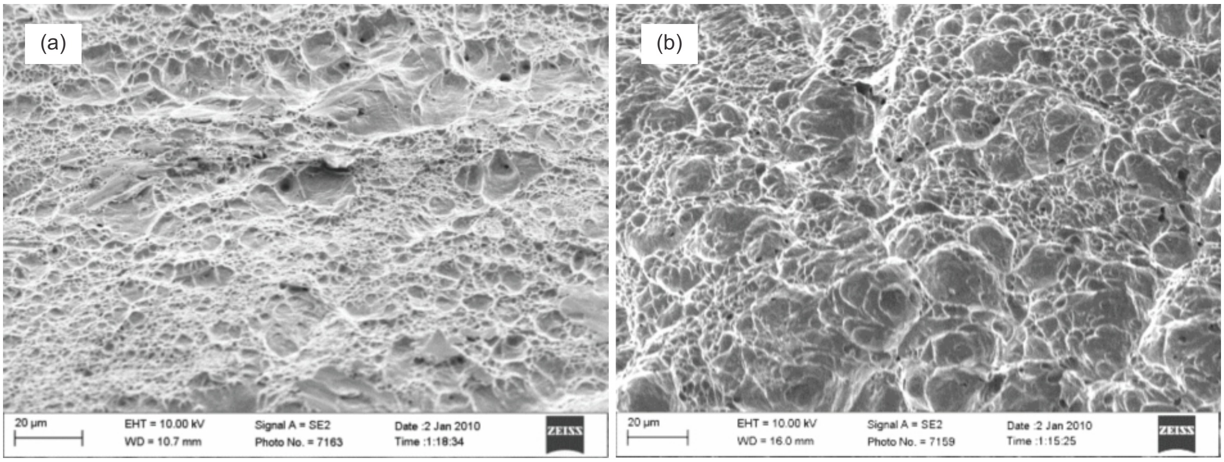

Fig.7 : Fractured charpy specimens of (a) FSW-HSLA-RT (b) FSW-HSLA-600

4.0 CONCLUSIONS

1. Thermal assisted friction stir welding is having significant effect on over all microstructural development and thereby, resultant mechanical properties of the friction stir welded steel.
2. A hard brittle zone was found, when the cooling rate is around 25 °C/s (FSW-HSAL-RT) and it changed to more tougher microstructure for the samples preheated at 300°C and 600°C and correspondingly having cooling rate of 8 °C/s and 3 °C/s respectively.
3. A hard zone is mainly consisting of martensitic island with lathe bainitic microstructure showing a hardness of 460 Hv, whereas the preheated FSW sample at 300°C and 600°C shows widmanstätten ferrite and upper bainitic microstructure having lower hardness of nearly 360 Hv.
4. The yield and ultimate tensile strength of friction stir welded with preheating was 10% more than the FSW-HSLA-RT sample. Similar trend was also observed for toughness property as FSW-HSLA-RT sample showed lowest charpy toughness due to hard brittle martensitic zone.
5. Fractography studies on broken charpy toughness samples indicate quasi cleavage mixed mode fracture features in FSW-HSLA-RT sample, whereas ductile dimples were observed in preheated samples (FSW-HSAL-300 and FSW-HSLA-600) and thus, indicate more energy absorbed during impact testing

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