Effect of Welding Parameters on Microstructure and Mechanical Properties of Friction Stir Welded Plain Carbon Steel

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In the present investigation, friction stir welding was carried out for plain carbon steel under variable rotational and traversing speed of tool keeping all other welding parameters same. Microstructural characterization was carried out for welded samples along with determination of microhardness distribution and evaluation of mechanical properties. Weld nugget microstructure principally consisted of ferrite-pearlite, however ferrite grain size and pearlite area fraction were varied depending on welding parameters. Substantial grain growth was found in heat affected zone. Sub-size tensile specimens exhibited improvement in strength; whereas, standard tensile samples showed lowering in strength with respect to parent alloy. Ductility of subsize and standard specimens showed smaller value in comparison to parent alloy and dependent on local microstructural characteristics.

KEY WORDS: friction stir welding; carbon steel; microstructure; mechanical properties.

1. Introduction

As a major structural item usage of steel in different dimension is inevitable. Fabrication of components using steel needs joining. Conventional fusion welding of steel suffers from grain growth, segregation of alloying elements, solidification cracking, porosity, hydrogen embrittlement and dendritic structure development leading to loss of component integrity.1,2) In that respect, friction stir welding (FSW) of steel as a solid state joining offers green technology with low heat generation, minimal component distortion, negligible pollution, and ease of automation.3) However, commercial application of FSW to ferrous alloys has not yet been achieved widely due to lack of availability of economic tool material which can withstand high plunging load i.e. encountered at elevated temperature during welding. T. J. Lienert et al.3) have carried out FSW for 1 018 carbon steel under different tool traversing speed and observed, that temperature of stir zone became ~1 200°C during welding. They reported that depending on local thermo-mechanical condition different zones were developed. In a different endeavor, single and double sided FSW of RQT-701 steel exhibited bainitic-martensitic microstructure at weld nugget (WN) with minimum hardness at heat affected zone.5) DH36 steel was friction stir welded under variable traversing speed using WC tool and the presence of martensite-bainite at weld nugget was reported.6) Microstructural evolution during friction stir welding of API grade X80 and L80 carbon steel was studied in details in co-relation with microhardness distribution.7) The study showed, that microstructure of thermo-mechanically affected zone (TMAZ) was consist of granular bainite, degenerated upper bainite and tempered martensite. Friction stir welding of high carbon steel (~0.72%C) with ferrite-pearlite structure highlighted, that tool rotation and traversing speed had pre-dominant effect on weld nugget microstructure and influenced hardness profile significantly.8) Friction stir welding of steel with different carbon content (0.12–0.50%C) was also studied.9) The strength of all welds was increased substantially after FSW in longitudinal direction. Ferrite-pearlite structure was obtained for carbon content ≤0.12% and critical cooling rate for carbon content ≥0.12% yielded martensitic structure at nugget. Lowering in heat input facilitated the process without phase transformation and resulted in considerable grain refinement. Sato et al. has attempted friction stir welding of ultrahigh carbon steel (1.02%C) with starting microstructure of spheroidized cementite dispersion in ferrite matrix.10) They indicated, that welding steered solid state phase transformation to produce martensite at weld nugget and duplex structure along with small quantity of martensite at HAZ. One of the present authors investigated friction stir weldability of advanced high strength steel recently and co-related total amount of strain generation with prior austenite grain size at weld nugget and ZH parameter through empirical relationship.11)

From above illustrations, it is evident that a number of attempts have been made so far for joining steel of different grades; however information available is incomplete in terms of microstructure and mechanical properties as too many variations are there in process window and composition. For any particular steel, apart from feasibility study, optimized processing parameters are required for its efficacious commercial usage. Therefore, in present investigation plain carbon steel has been chosen, systematically welding

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parameters were varied, microstructure was investigated and mechanical properties were evaluated to obtain welding window which can deliver best quality joint.

2. Experimental

Plain carbon steel with dimension 150 mm length × 50 mm width × 2 mm thickness was taken for FSW. The substrate microstructure was ferrite-pearlite with ferrite grain size of \( \sim 10 \pm 1 \ \mu m \) and pearlite area fraction \( \sim 14 \pm 2\% \). Chemical composition and mechanical properties of the alloy are summarized in Tables 1 and 2, respectively.

Butt joints were made using position control mode under different tool rotational and traversing speed. Tungsten carbide tool was used for welding. Shoulder and cylindrical probe diameter was \( \sim 15 \ \text{mm} \) and \( \sim 3.5 \ \text{mm} \) respectively. Pin length was \( \sim 1.4 \ \text{mm} \) and tool tilt angle was \( \sim 2.5^\circ \). Welding condition and sample nomenclature are listed in Table 3.

Microstructure of transverse section of welds was studied by optical microscope. Grain size and area fraction of phase were determined using image analyzing software considering six different frames taken from different locations for a single sample. Microhardness profile across weld centre was obtained at a depths of \( \sim 0.5 \ \text{mm} \) from surface under 0.1 Kgf load. Tensile testing was done on two different set of samples; one was with gauge length \( \sim 15 \ \text{mm} \) and the other was \( \sim 40 \ \text{mm} \). For the first and second set, thickness of tensile sample was \( \sim 0.4 \ \text{mm} \) and \( \sim 1.8 \ \text{mm} \) respectively. The test

| Table 1. Chemical composition of steel (wt%). |
|-----------------------------------------------|
| Alloy | C   | S   | P   | Si  | Mn  | Cr  | Cu  | Ni  | Fe  |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| C-Steel | 0.44 | 0.08 | 0.024 | 0.66 | 2.81 | 0.16 | 0.77 | 0.02 | bal |

| Table 2. Mechanical properties of steel at ambient temperature. |
|---------------------------------------------------------------|
| Alloy | Ultimate tensile strength (MPa) | Elongation (%) | Hardness (VHN) |
|-------|---------------------------------|----------------|----------------|
| C-Steel | 435 ± 3 | 23.8 ± 1.7 | 160 ± 2 |

| Table 3. Sample identification and welding condition. |
|-----------------------------------------------------|
| Sample I.D. | Tool rotation (rpm) | Tool traversing speed (mm/min) |
|-------------|---------------------|-------------------------------|
| Sample-1    | 710                 | 100                           |
| Sample-2    | 900                 | 100                           |
| Sample-3    | 1120                | 100                           |
| Sample-4    | 900                 | 67                            |
| Sample-5    | 900                 | 150                           |

Fig. 1. Friction stir welded steel sheet (a) as welded specimen, and (b) cross section of weld.

Fig. 2. Optical micrographs of weld nugget (a) 710 rpm_100 mm/min, (b) 900 rpm_100 mm/min, (c) 1120 rpm_100 mm/min, (d) 900 rpm_67 mm/min, and (e) 900 rpm_150 mm/min.
was performed as per ASTM specification of E8M-96 at across head speed of 0.5 mm/min and fracture location was identified. The philosophy of testing samples of two different gauge lengths was to explore weld nugget and assembly mechanical properties separately. For each parameter three samples were tested to check reproducibility of results.

3. Results

Friction stir welded specimen is shown in Fig. 1(a) along with macro image in Fig. 1(b). Bowl shape region indicates weld nugget which under goes severe plastic deformation owing to both shoulder and pin effect. Outside of weld nugget, a thin area is formed and termed as heat affected zone (HAZ), where the region only experiences thermal effect due to heat dissipation. Outside of HAZ, it is base material. Typical thermo-mechanically affected zone was not observed in present study, as deformation during FSW was accompanied by allotropic transformation and characteristic of this zone was lost within HAZ and WN.4) Presence of different phases in welded joints depends on local thermal condition i.e. temperature rise and cooling rate. Detailed

| Sample ID | WN | HAZ |
|-----------|----|-----|
|           | Grain size (μm) | Pearlite area fraction (%) | Grain size (μm) | Pearlite area fraction (%) |
| 900 rpm-150 mm min⁻¹ | 5.6 ± 0.7 | 22.4 ± 1.2 | 11.1 ± 0.3 | 18.6 ± 1.4 |
| 900 rpm-100 mm min⁻¹ | 6.2 ± 0.1 | 21.1 ± 2.6 | 11.3 ± 0.2 | 18.1 ± 1.7 |
| 900 rpm-67 mm min⁻¹ | 6.7 ± 0.1 | 19.9 ± 0.9 | 11.7 ± 0.1 | 17.4 ± 2.5 |
| 710 rpm-100 mm min⁻¹ | 5.9 ± 0.1 | 23.3 ± 0.7 | 10.3 ± 0.2 | 15.3 ± 2.2 |
| 1120 rpm-100 mm min⁻¹ | 8.2 ± 0.7 | 17.3 ± 1.3 | 15 ± 0.1 | 16.8 ± 2.8 |

Fig. 3. Optical photographs of HAZ (a) 710 rpm_100 mm/min, (b) 900 rpm_100 mm/min, (c) 1120 rpm_100 mm/min, (d) 900 rpm_67 mm/min, and (e) 900 rpm_150 mm/min.

Fig. 4. Optical images of different regions for 710 rpm_100 mm/min welded specimen (a) voids at a glance, (b) voids within WN, and (c) voids at HAZ.
microstructure is discussed in subsequent sections.

Optical micrographs of weld nugget are shown in Figs. 2 (a)–2(e). Microstructure of all joints revealed bright polygonal ferritic grains in combination with shaded unresolved pearlitic colony. Friction stir welding of mild steel reported formation of ferrite with aligned and non-aligned second phase, grain boundary ferrite, ferrite-carbide aggregate in the form of fine pearlite at stir zone. Fujii et al. has also indicated occurrence of ferrite-pearlite during friction stir welding of S35C carbon steel at 400 rpm, 100–400 mm/min. Average grain size of ferrite and area fraction of pearlite vary at weld nugget depending on welding parameter and data is collated in Table 4. As depicted in microhardness profile, average microhardness of weld nugget was ~200–250 VHN, which indicated substantial increment with respect to base alloy (Fig. 5). Uniform microhardness distribution across weld nugget indicated homogeneous microstructure on both sides of run centerline. Away from weld centre line, heat affected zone exhibits polygonal ferrite and pearlite at grain boundary triple point (Fig. 3). Coarsening

Fig. 5. Microhardness distribution across the weld line (a) 710 rpm_100 mm/min, (b) 900 rpm_100 mm/min, (c) 1120 rpm_100 mm/min, (d) 900 rpm_67 mm/min and (e) 900 rpm_150 mm/min.

Fig. 6. Tensile properties of welds (a) sub-size, 100 mm/min traversing speed (b) sub-size, 900 rpm rotational speed, (c) standard, 100 mm/min traversing speed, and (d) standard, 900 rpm rotational speed (firm line UTS & dotted line Elongation).
of grain size, in this region resulted in drop in average microhardness value (~150–165 VHN) with respect to weld nugget. (Fig. 5). Additionally, the sample, welded at 710 rpm_100 mm/min, displayed few discontinuities at WN and its surrounding areas (Figs. 4(a)–4(c)). This type of voids was not found for any other samples.

Mechanical properties are furnished in Figs. 6(a)–6(d). Sub-size tensile specimens represented mechanical behavior of WN only and standard specimens indicated mechanical property of transition joint containing WN, HAZ and base metal. Sub-size specimens exhibited more or less improvement in bond strength with respect to base material except 710 rpm_100 mm/min. Improvement is remarkable at intermediate rotation and high traversing speed of tool. Standard samples showed lowering in assembly strength with respect to base alloy. The drop was marginal at 900 rpm and substantial at 1 120 rpm. The ductility of samples of two different geometries was ~50% of that of parent alloy.

4. Discussion

Microstructure in different regions of joint depends on welding parameters. More specifically, peak temperature and cooling rate control prior austenite grain size, pro-eutectoid ferritic grain size, area fraction of pearlite and interlamellar spacing of pearlite. As discussed in literature, weld nugget experiences thermal and mechanical effect from both pin and shoulder.\(^{13}\) On the other hand, microstructure of HAZ is influenced indirectly by thermal effect of shoulder without any mechanical deformation.\(^{14}\) Temperature rise at WN is pre-dominantly governed by rotational speed of tool.\(^{15}\) It has been indicated previously, that rotational speed of ≥900 rpm during FSW of steel raised stirring zone/weld nugget temperature to ≥1 000°C.\(^{16}\) At ~800 rpm, peak temperature at WN was dropped and became ~900°C.\(^{8}\) Therefore, for 760–1 120 rpm of tool, weld nugget of carbon steel transformed to single phase austenite and subsequently to ferrite-pearlite during cooling. Higher will be rotational speed, more will be total heat input, greater will be peak temperature and larger will be austenite grain size. The cooling rate is increased with enhancement in tool traversing speed and it has predominant effect on grain size of final microstructure. At constant traversing speed, when rotational speed was increased from 760 to 1 120 rpm, increment in austenitic grain size reduces grain boundary area as well as preferable site for nucleation of pro-eutectoid ferrite; therefore ferrite grain size gradually increases at WN (Table 4). Similarly, small quantity of ferrite-austenite interface provided limited nucleation sites for pearlite and area fraction of same was decreased. However, owing to more or less same cooling rate at same tool traversing speed, interlamellar spacing will not change for pearlite. So, considering the combined effect of ferrite grain size and pearlite area fraction, the strength of weld nugget initially increased, reached consummate point and then decreased with increment in tool rpm at constant traversing speed (Fig. 6(a)). However, weld nugget grain size was lower than base alloy owing to severe plastic deformation accompanied by dynamic recrystallization.\(^{10}\) Hence, an overall improvement in tensile strength was found with respect to parent alloy. Cooling rate was increased with increment in tool traversing speed at a constant tool rotation. It reduced time for carbon diffusion and increased carbon content in austenite resulting in lower transformation temperature. Interlamellar spacing of pearlite was decreased and pearlite became finer. At the same time, higher cooling rate provided higher driving force for more number of nucleation sites for ferrite; matrix grain size thus became finer. Weld nugget strength was improved and became ~110% of that of parent alloy (Fig. 6(b)). The effect of traversing speed of tool was negligible in HAZ; therefore grain size was only influenced by heat dissipation from WN through this region without any deformation effect of tool. Pearlite lamellar spacing or area fraction was more or less same under normal cooling in air. Grains in HAZ showed an over all growth during welding and became larger than base alloy. Though the pearlite area fraction in this region is greater than parent alloy, still grain growth was responsible for lowering in tensile strength of assembly as a whole in comparison to parent alloy (Figs. 6(c)–6(d)). The ductility of both sub-size and standard specimen was low with respect to base material. Low ductility at weld nugget may be attributed to excessive longitudinal tensile and transverse compressive residual strain generation during welding.\(^{4,5}\) High dislocation density has been depicted in transmission electron microscopy investigation of stir zone for friction stir welded plain carbon steel.\(^{16}\) These strains are generated owing to heating and subsequent cooling during welding accompanied by restricted material flow by the surrounding material and tool shoulder during welding. Most of the sub-size samples failed near center of gauge length. For standard sample, it was through HAZ/HAZ-base metal interface. In this respect present investigation contradict with earlier reports.\(^{4,6}\) Previous investigations stated that failure was from base material and bond strength was close to parent alloy. In the present study, as stated before, increment in HAZ grain size lowered the strength of welded joints and all of them exhibited lower bond strength with respect to parent alloy. 710 rpm_100 mm/min sample showed scattered porosity (~5–25 μm) within weld nugget and HAZ (Figs. 4(a)–4(c)). Perhaps these welding parameters were not appropriate for proper material transport during FSW of this alloy leading to discontinuity owing to incomplete filling of cavity. Failure under tensile loading occurred through the porosity and both sub-size and standard samples displayed poor bond strength.

5. Summary

Friction stir welding was carried out for carbon steel plate under tool rotation and traversing speed in the range of ~760–1 120 rpm and ~67–150 mm/min, respectively using tungsten carbide tool. Following inferences are made from the investigation:

(1) FSW developed two distinct regions within welded region, i.e. weld nugget and heat affected zone. Weld nugget microstructure was consisted of ferrite and pearlite. Ferrite grain size and pearlite area fraction were dependent on local thermo-mechanical condition. High rotational speed and low traversing speed of tool enhanced ferrite grain growth. Pearlite area fraction dropped either with decrease in tool traversing rate or with increase in tool rpm.

(2) Microstructure of heat affected region was influ-
enced by induced thermal effect of weld nugget, *i.e.* influenced mainly by tool rotation. HAZ microstructure was also ferrite-pearlite; however grain growth occurred and grain size was larger than parent alloy.

(3) Overall decrement in grain size with increased area fraction of pearlite at weld nugget resulted in betterment in tensile strength (>100%) of subsize specimens with respect to as received steel. However, strength of standard specimens exhibited a lower trend with respect to parent alloy owing to grain growth in HAZ.

(4) Ductility of subsize and standard specimens showed smaller value in comparison to parent alloy because of high defect density at WN and grain growth at HAZ respectively.

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