The present investigation is aimed at studying the effect of autogenous arc welding processes on fatigue crack growth of the ferritic stainless steel conforming to AISI 409M grade. Rolled plates of 4 mm thickness were used as the base material for preparing single pass butt welded joints. Tensile, impact and fatigue properties, micro hardness, microstructure and fracture surface morphology of the continuous current gas tungsten arc welded, pulsed current gas tungsten arc welded and plasma arc welded joints were evaluated and the results are compared. From this investigation, it is found that plasma arc welded joints of ferritic stainless steel showed superior fatigue performance compared with continuous current gas tungsten arc welded and pulsed current gas tungsten arc welded joints and this is mainly due to the superior mechanical properties, preferred microstructures in the fusion zone region and favourable residual stress field in the fusion zone region.

KEY WORDS: ferritic stainless steel; plasma arc welding; continuous gas tungsten arc welding; pulsed current gas tungsten arc welding; impact and fatigue properties.
The present investigation was carried out to understand the effect of autogenous arc welding techniques on fatigue properties of ferritic stainless steel joints.

2. Experimental Work

The rolled plates of 4 mm thickness AISI 409M grade ferritic stainless steel were cut into the required dimension (300x150 mm) by oxy-fuel cutting and grinding. The chemical composition of base metal is presented in Table 1. The initial joint configuration was obtained by securing the plates in position using tack welding. Square butt joints were fabricated using autogenous arc welding (without filler metal addition) processes such as Continuous Current Gas Tungsten Arc Welding (GTAW), Pulsed Current Gas Tungsten Arc Welding (PCGTAW) and Plasma Arc Welding (PAW). All necessary care was taken to avoid joint distortion and the joints were made with applying clamping devices. The welding conditions and process parameters used to fabricate the joints are given in Table 2. The soundness of all the welded plates was checked using ultrasonic testing.

The welded joints were sliced using power hacksaw and then machined to the required dimensions for preparing tensile, impact and fatigue test specimens as shown in Fig. 1. Tensile test was conducted in 100 kN, electro-mechanical controlled Universal Testing Machine. ASTM E8M-04 guidelines were followed for preparing and testing the tensile specimens. Since the plate thickness is small, subsize impact specimens were prepared. Impact test was conducted at room temperature using pendulum type impact testing machine with a maximum capacity of 30 J. ASTM E23-04 specifications were strictly followed for preparing and testing the specimens.

For Centre Cracked Tensile (CCT) specimen, the sharp notch was machined in the fusion zone region to the required length using the wire cut electric-discharge machine (EDM). Procedures prescribed by the ASTM E647-04 standard were followed for the preparation of the specimens. Fatigue crack growth experiments were conducted using a servo hydraulic, 100 kN universal testing machine. A frequency of 20 Hz under constant amplitude loading (R=0) was used for all fatigue tests. Before loading, the specimen surface near the notch was polished to facilitate fatigue crack growth measurement. A traveling microscope with an accuracy of 0.01 mm was used to monitor the crack length. The specimen was loaded at a particular stress level (range), and following crack initiation from the tip of the machined notch, its subsequent propagation into the weld metal was recorded from initiation to the complete failure of the specimen. Similar crack growth experiments were conducted on a number of specimens at various stress levels, and the experimental data were recorded.

Vicker’s microhardness testing machine was employed for measuring the hardness of the weld with 0.5 kg load. Microstructural examination was carried out using a light optical microscope incorporated with image analyzing software. The specimens for metallographic examination were sectioned to the required size from the joint comprising fusion zone region and were polished using different grades of emery papers. Final polishing was done using the diamond compound (1 μm particle size) in the disc polishing machine. The specimens were etched with 5 mL hydrochloric acid, 1 g picric acid and 100 mL methanol applied for 10–15 s. The fractured surface of the fatigue tested specimens was analysed using Scanning Electron Microscope at higher magnification to study the fracture morphology to establish the nature of the fracture.

Table 1. Chemical composition of base metal.

| Elements | C   | Mn | P   | S   | Si   | Cr   | Ni   | Ti   | Mo | Cu | Fe |
|----------|-----|----|-----|-----|------|------|------|------|----|----|----|
| Base metal (AISI 409M) | 0.028 | 1.10 | 0.030 | 0.010 | 0.40 | 10.90 | 0.39 | 0.004 | -- | -- | Bal. |

Table 2. Welding conditions and process parameters.

| Parameters  | Square butt joint fabrication |
|-------------|-------------------------------|
| CCGTAW      | PCGTAW                        | PAW |
| Arc Voltage (volts) | 24 | 24 | 24 |
| Welding Current (amps) | 150 | 150 | 150 |
| Welding Speed (mm/min) | 200 | 200 | 300 |
| Heat Input (J/mm) | 1080 | 900 | 720 |
| Gas Flow Rate (l/min) | 14 | 14 | 18 |
| Electrode Diameter (mm) | 3 | 3 | 2.5 |

Fig. 1. Dimensions of tensile, impact and fatigue specimens.
3. Results

3.1. Tensile and Impact Properties

The transverse tensile properties such as yield strength, tensile strength and percentage of elongation of FSS joints were evaluated. In each condition, three specimens were tested, and the average of three results is presented in Table 3. Of the three welded joints, the joints fabricated by P AW process exhibited higher strength values, and the enhancement in strength value is approximately 35% compared to PCGTAW joints and 40% compared to CCGTAW joints. Charpy impact toughness values of all the joints were evaluated and they are presented in Table 3. The impact toughness of unwelded base metal is 22 J. Of the three welded joints, the joints fabricated by P AW process exhibited higher impact toughness values, and the enhancement in toughness value is approximately 25% compared to PCGTAW joints and 50% compared to CCGTAW joints.

3.2. Hardness and Microstructure

Vickers micro hardness measured at the fusion zone region of the joints is presented in Table 3. The hardness of the CCGTAW and PCGTAW joints in the fusion zone region is 306 VHN and 354 VHN respectively. However, the hardness of the PAW joints in the fusion zone region is 410 VHN, which is relatively higher compared to CCGTAW and PCGTAW joints. The optical micrographs of fusion zone region of autogeneous arc welded joints are presented in Fig. 2. The fusion zone (FZ) region primarily consists of ferrite grains. From the micrographs, it is understood that there is an appreciable difference in grain size (average grain diameter) in the fusion zone regions. Hence, an attempt was made to measure the average grain diameter of the fusion zone of all the joints applying Heyn’s line intercept method [ASTM E112-04, 2006]. The measured average grain diameter of CCGTAW joints is 40 μm, but the average grain diameter of PCGTAW joints is 25 μm. This indicates that reduction in grain diameter is 15 μm due to the pulsed current welding process. Similarly the measured average grain diameter of PAW joints is 10 μm, and this also indicates that the reduction in grain diameter is 30 μm due to the PAW process. Of the three techniques, the PAW process produced fine grains in the fusion zone region compared with the CCGTAW and PCGTAW processes.

3.3. Fatigue Properties

The fatigue crack growth experiments were conducted at five different stress levels ($\Delta\sigma$) of 75, 100, 125, 150 and 175 MPa and under constant amplitude loading conditions ($R=0$). The measured variation in crack length ($2a$) and the corresponding number of cycles ($N$) endured under the action of particular applied stress range are plotted as shown in Fig. 3 for all the joints. The fracture mechanics based Paris Power equation, Eq. (1), given below, was used to analyse the experimental results.

$$\frac{da}{dN} = C(K)^m \quad \text{(1)}$$

Where $da/dN$, crack growth rate; $\Delta K$, stress intensity factor (SIF) range; ‘$C$’ and ‘$m$’ are constants. The SIF value was calculated for different values of growing fatigue crack length ‘$2a$’ using the following expression (2)

$$\Delta K = \phi(\Delta\sigma)\sqrt{\pi a} \quad \text{(2)}$$

However, the geometry factor for the CCT specimen was calculated using the expression (3) given below

$$\phi = F(\alpha) = \sec \left( \frac{\alpha}{2} \right) \quad \text{(3)}$$

The crack growth rate, $da/dN$ for the propagation stage was calculated for the steady state growth regime, at different intervals of crack length increment, against the associated number of cycles to propagation. The relationship between SIF range and the corresponding crack growth rate in terms of best fit lines is shown in Fig. 4 for all the joints. The data points plotted in the graph mostly correspond to the second stage of Paris sigmoidal relationship ($10^{-6}$ to $10^{-3}$ mm/cycle). The exponent ‘$m$’, which is the slope of the line on log–log plot and the intercept ‘$C$’ of the line, has been determined and they are presented in Table 4.
When the crack growth rate is around $10^{-3}$ mm/cycle, the curve tends to become parallel to the $Y$-axis, and the corresponding $\Delta K$ value is taken as critical ($\Delta K_{cr}$). At lower values of $\Delta K (10^{-5})$, the curve again becomes parallel to the $Y$-axis, indicating a threshold $SIF (\Delta K_{th})$ below which a crack may not propagate. The values of $\Delta K_{cr}$ and $\Delta K_{th}$ for all joints have been evaluated and are presented in Table 4. Normally, in the case of steels, the threshold value is obtained for a crack growth rate of $10^{8}$ mm/cycle. Due to the specimen configuration and loading conditions, crack propagation rates in the region of $10^{8}$ mm/cycle could not be obtained, and hence the value obtained in this analysis cannot be taken as the design value. The fatigue crack growth (fracture mechanics) parameters of all the joints are compared in Table 4.

It is also advantageous to determine the standard $S-N$ curve for the test conditions, which will indicate the trend and also be useful for design purposes. Figure 5 shows the relationship between stress range and the number of cycles to failure on a log–log plot for all the joints. The stress corresponding to $2 \times 10^{6}$ cycles is taken as an indication of the endurance limit, and these values are determined for all the joint combinations and are presented in Table 4.

Each endurance line can be represented by a Basquin type equation, in general form, as expressed below:

$$N_i = A(\Delta \sigma)^{-n}$$  \hspace{1cm} (4)

Where ‘$A$’ and ‘$n$’ are constants (‘$n$’ is slope of the line and ‘$A$’ is intercept of the line) and their values are evaluated and presented in Table 4.

### 3.4. Fracture Surface

The fatigue fracture surface appearance corresponding to crack initiation, crack propagation and the final failure regions of the joints (100 MPa alone), as observed under the Scanning Electron Microscope (SEM) is displayed in Fig. 6. The fatigue crack initiation region (FCI) is corresponding to 1 mm from the tip of the machined notch; fatigue crack propagation (FCP) region is referred to 1 to 6 mm; final failure (FF) region is referred to 6 mm away from the crack initiation region. In all the FCI regions, the crack initiations sites are clearly visible and it can be observed from the fractographs that the fatigue cracks have initiated from multiple crack initiation sites. Apart from this, there is no specific, noticeable characteristic feature has been observed in the FCI region of all the joints and it can be concluded

| Joints   | $m$   | $C$   | $n$ | $A$  | $\Delta K_{cr}$ | $\Delta K_{th}$ | $\Delta \sigma$ |
|----------|-------|-------|-----|------|-----------------|-----------------|----------------|
| BM       | 3.99  | 5.4x10^{11} | 1.79 | 4.8x10^{10} | 7.0             | 40              | 120            |
| CCGTAW   | 5.15  | 2.6x10^{11} | 2.93 | 1.8x10^{11} | 5.0             | 20              | 90             |
| PCGTAW   | 4.88  | 2.28x10^{10} | 2.51 | 1.5x10^{11} | 5.5             | 25              | 100            |
| PAW      | 4.25  | 8.41x10^{10} | 1.97 | 6.4x10^{10} | 6.0             | 30              | 110            |

Table 4. Fatigue parameters of autogenous arc welded ferritic stainless steel joints.
that the fracture surface is featureless in FCI region and it depends on material, welding processes, filler metal, loading conditions, environment etc.

Invariably in FCP regions (where steady state crack growth occurs) of all the joints, the micro-level striations were observed and the spacing between the micro-level striations varies in each joints. Very closely spaced striations are seen in PAW joint compared to their counterparts. From the fractographs of final failure region, it is observed that the tear dimples are elongated along the loading direction and this is mainly because of the limit load condition at the time of final fracture. Even though unstable crack growth occurs in the final failure region, the final fracture is still in the ductile mode and it is evident from the presence of dimples. But the shape and size of the dimples are different in all the joints and it is influenced by the grain size of the fusion zone region.

3.5. Residual Stresses

Table 5 shows the measured residual stress values. In the CCT specimens, the measured residual stress values are in compressive and this is mainly due to the reason that after welding the joints were sliced, machined and ground to obtain the required dimensions of CCT specimen. Because of the above mentioned machining operations, the original tensile residual stresses caused by welding operation are relieved and subsequently, compressive stress fields are generated due to the compressive load acted on the specimen during grinding operation.

| Joint Type | Magnitude of residual stress in the weld metal (WM) region, MPa |
|------------|----------------------------------------------------------|
| CCGTAW     | +150                                                     |
| PCGTAW     | +125                                                     |
| PAW        | +115                                                     |

4. Discussion

The fatigue crack initiation behaviour, fatigue crack growth behaviour and fatigue life of the ferritic stainless steel joints are influenced by the autogenous arc welding processes. Of the three joints, PAW joints are offering higher fatigue resistance than CCGTAW and PCGTAW
welded joints. In the CCT specimen, the notch is machined in the fusion zone region of the joints by wire cut EDM (electric discharge machining) process to evaluate the crack growth behaviour of the welded joints under fatigue loading. The fatigue crack initiates from the tip of the machined notch and it grows in the fusion zone region until final failure takes place and hence the tensile and impact properties of fusion zone, hardness and microstructure of fusion zone and residual stress pattern in fusion zone will have greater influence on fatigue performance of the joints. The effect of these properties on fatigue behaviour has been discussed in the following sections.

4.1. Effect of Fusion Zone Microstructure

The weld region microstructure depends upon weld thermal cycles or in other words by heat input supplied by the welding process involved. CCGTAW process produces coarser grains compared to PCGTAW and PAW processes (Fig. 2). Fine grained microstructures relatively contain higher amount of grain boundary areas than coarse grain microstructure and in turn offer more resistance to fatigue crack propagation and this may be the reason for improved fatigue performance of PCGTAW welded joints compared to CCGTAW welded joints. The heat input supplied by the CCGTAW process is relatively higher than PCGTAW and PAW processes. The heat input involved in the PAW process is comparatively lower than CCGTAW and PCGTAW processes (Table 2). These variations in heat input of the welding processes influence the weld thermal cycle and subsequently causes variations in microstructural features and mechanical properties.

The fatigue properties of metals are quite structure sensitive. Optimization of the microstructural dimensions for improved resistance to both crack initiation and crack growth would require a trade-off in the choice of grain size or even the development of a structure with a distribution of grain sizes. In the near threshold regime of fatigue crack growth, where a significant portion of stable crack growth life is expended, an increase in grain size of the material generally results in a marked reduction in the near threshold fatigue crack growth rates and an increase in threshold SIF range. On the other hand, the resistance of a material to fatigue crack initiation, expressed in terms of an endurance limit, often increases with decreasing grain size and increasing strength of the material. Although these results may appear contradictory, they can be rationalized by noting that the former inference is valid solely for fatigue crack growth, especially at low stress intensity range levels, whereas the latter conclusion pertains primarily to crack initiation. If pre-existing flaws are not of a major concern, a finer grain size which promotes higher strength and higher endurance limit is favoured. On the other hand, if a defect-tolerant design is adopted and the flawed component is expected to be subjected to high frequency, low stress amplitudes, then fatigue crack growth, especially at low stress intensity range levels, whereas the latter conclusion pertains primarily to crack initiation. If pre-existing flaws are not of a major concern, a finer grain size which promotes higher strength and higher endurance limit is favoured. On the other hand, if a defect-tolerant design is adopted and the flawed component is expected to be subjected to high frequency, low stress amplitude loading over a prolonged time span, a coarser grained microstructure would be more appealing.12)

4.2. Effect of Tensile and Impact Strength

The tensile properties (yield strength, tensile strength and elongation) of PAW joints are superior as compared to their counterparts (see Table 3). Higher yield strength and tensile strength of the PAW joint is greatly used to enhance the endurance limit of the joints and hence the fatigue crack initiation is delayed. Larger elongation (higher ductility) and higher toughness (impact strength) of the PAW joints also impart greater resistance to fatigue crack propagation and hence fatigue failure is delayed. The combined effect of higher yield strength, higher ductility and higher toughness of the PAW joint offers enhanced resistance to crack initiation and crack propagation and hence the fatigue performance of the joints is superior as compared to their counterparts.

In the lower strength weld metal, as in the case of CCGTAW joints, since the deformation and the yielding are mainly concentrated in the fusion zone, the extension of the plastic zone is limited within the fusion zone. As soon as the plastic zone reaches the fusion line, plasticity keeps on developing along the interface between the base metal and fusion zone region.13) The triaxial state of stress is high in fusion zone region and the relaxation of this stress is poor. The crack driving force needed for crack extension is small. So, the fracture toughness of the lower strength weld metal is not high. On the other hand, if strength of the fusion zone is higher, the plastic zone can easily extend into the parent material because the deformation and yielding occur in both fusion zone and the base metal. The stress relaxation can easily take place in the crack tip region. So more crack driving force is needed for crack extension and the fracture resistance of the higher strength fusion zone region is greater than the lower strength fusion zone region.14) This is also one of the reasons for better fatigue resistance of the PAW joints.

4.3. Effect of Welding Residual Stresses

Residual stresses, which arise in welded joints as a consequence of incompatible thermal strains caused by heating and cooling cycles, also have significant effect on the fatigue life of welded structures.15) When a fatigue crack is propagating through a residual stress in welded plate, the stress intensity at the crack front is influenced by the combined effect of local residual stress and the stress resulted from externally applied stress. It means that the effective stress intensity factor of the crack front is sum of stress intensity factor due to residual stresses and the stress intensity factor due to external loading.16) In the presence of residual stresses, the CTOD (crack tip opening displacement) for a crack in higher strength weld metal was always larger than the value for a crack in homogeneous plate or lower strength weld metal at the same load.17)

In fusion welding, during heating cycle, the expansion of weld metal is resisted by the surrounding base metal but during cooling cycle, the contraction of weld metal is also resisted by the surrounding base metal. Due to the restraint offered by the base metal during expansion and contraction of weld metal, a tensile residual stress field is generated in the weld region.18) In fusion welding processes, the generation of residual stress field in the weldment mainly depends on the welding parameters such as arc voltage, welding current and welding speed and subsequently heat input of the welding process. If the heat input of welding process is higher, then the magnitude of tensile residual field in the weld region will be greater.
Of the three autogeneous fusion welding processes used in this investigation to fabricate the AISI 409M grade FSS, the heat input involved in CCGTAW process is relatively higher compared to PCGTAW and PAW processes. Hence the magnitude of tensile residual stress in CCGTA welded joints is higher compared to other joints and this is also evident from the measured residual stress values presented in Table 5. However, the pulsed current welding provides the cushioning effect to the weld metal between pulses (while varying from peak current to base current) and the stresses are relaxed between the pulses. Due to this advantage, the magnitude of residual stress in the pulsed current welded joints is lower as compared to continuous current welded joints. Moreover, the PCGTAW welded joint contains lower magnitude of tensile residual stress field in the weld region as compared to CCGTA welded joints.

Residual stresses are usually relieved during fatigue cycling due to high strains/stress concentrations around the crack front. However, in this investigation the applied stress range is 75–175 MPa which is much lower than the yield strength of the weld metals as well as base metal. Hence, the stresses and stress concentrations along the crack front were not high and as a result they were not relieved during fatigue cycling. Moreover, the residual measurement was carried out mainly to understand the effect of heat input of welding processes and also to know the initial condition (stress state) of the test specimens.

Even though the compressive load acts on the specimen during grinding is uniform, the resultant residual stress values are different and this may be due to the differences existed in the original (as welded condition) tensile residual stress values. From the measured residual stress values (Table 5), it can be inferred that the magnitude of resultant compressive stress field in plasma arc welded (PAW) CCT specimen is relatively higher than CCGTA and PCGTAW welded specimens. This may be the reason for slower fatigue crack growth rate observed in PAW joints since compressive residual stresses usually retard the rate of fatigue crack growth.19,20)

5. Conclusions

The present investigation was carried out to study the effect of autogenous arc welding processes on fatigue crack growth behavior and fatigue life of ferritic stainless steel. From this investigation, the following conclusions have been obtained:

(1) Lower heat input, finer fusion zone grain diameter, higher fusion zone hardness may be the reasons for superior tensile and impact properties of PAW joints compared to CCGTAW and PCGTAW processes.

(2) The fatigue performances of plasma arc welded joints are superior compared to the continuous current welded and pulsed current welded gas tungsten arc welded joints.

(3) The superior mechanical properties (higher yield strength and toughness), preferred microstructures in the fusion zone region (very fine equiaxed grains) and favourable residual stress field in the fusion zone region (large magnitude of compressive stress) are the reasons for better fatigue performance of autogenous plasma arc welded ferritic stainless steel joints.

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