Interfacial microstructure and mechanical properties of Fe-36Ni invar alloy GTAW joint

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A 12 mm thickness invar alloy plate was multi-pass welded using commercial welding wire. Microstructures of the joint were examined by optical microscope (OM) and scanning electron microscope (SEM). The mechanical properties and microhardness of the joint were evaluated. Semi-elliptical band structures were formed in the weld zone, which was related to the interrupted cooling during weld pool solidification process. Ductility dip crack (DDC) was discovered at the grain boundaries of the joint and heated affected zone (HAZ), which is related to sulfur segregation at the grain boundary during the reheating process of multi-pass welding. The tensile strength and elongation of the joint reached 95.8% and 46.4% of the base material, respectively. The fracture position was found on the weld seam.

Keywords: Invar alloy, GTAW, microstructure, Tensile strength, Microhardness

As a typical functional material, invar alloy has been widely used in space remote sensors, satellites, ocean-going liquefied natural gas tankers and waveguides fields due to its low constant thermal expansion coefficient (TEC) under its Curie temperature (about 230°C), good ductility, excellent mechanical property and good corrosion resistance. In these applications, welding is used as the main joining method. So far arc welding, laser beam welding (LBW), soldering and friction stir welding (FSW) are main joining methods for invar alloys. Among these arc welding is the most convenience method to join invar alloy in the industry.

Some austenitic alloys undergo a severe ductility drops at temperatures between 0.5 and 0.7 of their melting temperature, which was defined as brittle temperature range (BTR) or Ductility dip temperature range (DTR). The fully austenite material suffers high sensitivity to hot cracking, i.e., solidification cracking, liquation cracking and ductility dip cracking (DDC). Invar alloy contains approximately 64% Fe and 36% Ni, which has austenitic microstructure. It has been reported that invar alloy has a strong tendency of hot cracking in the welding pool during the fuse welding. Especially, if the filler contents or welding parameters are selected improperly, hot cracking will form at the weld seam or heat affected zone (HAZ). Invar alloy also exhibits superior weldability with low heat input because of its low melting temperature and specific heat capacity. Gas tungsten arc welding (GTAW) is often used to increase hot cracking resistance of invar alloy due to its low heat input. However, during the welding of thicker plate higher heat input should be employed for multi-pass welding. In a typical multi-pass welding process, when one bead is affected by the thermal cycle of the second pass, a new problem, reheat cracking or ductility dip cracking or DDC can be arised which will further generate hot cracking. Literature show that DDC of invar joint is related to sulfur (S) concentration in the grain boundary (GB) in a welding zone or HAZ. The addition of both of Ti, Mn, Mo, Nb and C in the filler is beneficial to prevent the hot cracking in weld.

In this work, a filler metal with lower S and P content is used to weld invar alloy with GTAW. The cross-sectional microstructures of sample were observed by optical microscope (OM) and scanning electron microscope (SEM). The micro hardness and tensile strength of the joints were tested. The metallurgical phenomena related to welding process and the reheat cracking were observed and clarified.

Materials and Methods

The base material (BM) used in the present work is commercial invar alloy plate with a thickness of 12 mm. The filler metal used in the experiment is INVAR@M93 welding wire from Arcelor Mittal Company. The chemical compositions of the
investigated invar alloy and welding filler wire are summarized in Tables 1 and 2. The microstructure of the invar alloy is shown in Fig. 1.

Multi-pass GTAW was conducted manually on invar alloy plate with a double ‘V’ shape groove. The groove type and deposition sequences are shown in Fig. 2. The welding condition for specimen is given in Table 3.

The cross-sectional microstructures of weld were characterized by optical microscope (OLYMPUS-BX51M) and scanning electron microscopy (JEOL JSM-6460). Chemical compositions of various

<table>
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<th>Table 1 — The chemical compositions of Invar alloy (wt%)</th>
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<td>Element</td>
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<tr>
<td>Min</td>
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<td>Max</td>
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<th>Table 2 — The chemical compositions of INVAR@M93 (wt%)</th>
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<tr>
<td>Element</td>
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<td>Invar@93</td>
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<th>Table 3 — The welding parameters of invar alloy</th>
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<td>Welding Sequences</td>
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<tr>
<td>Upper back welding</td>
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<tr>
<td>Lower back welding</td>
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<tr>
<td>Upper cosmetic welding</td>
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<tr>
<td>Lower cosmetic welding</td>
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regions of the fusion zone were examined through energy dispersive spectrometer (EDS). The microhardness (Hv) test was conducted on the sample with an indentation load of P = 100 N and a dwell time of t=10 s using a micro-Vickers hardness tester (MHT SERIE 200). The tensile strengths of the joints were evaluated by standard tensile test with micro tester (Instron 5548).

**Results and Discussion**

**Microstructures of the joint**

The microstructures of the GTAW joint were observed by optical microscope (OM). Figure 3a shows the macro morphology of the cross-section of the joint. It can be seen that the double ‘V’ shaped weld formed without obvious pores and macro cracks. To observe the microstructures of different weld zones, five typical zones of the joint were chosen to be examined by OM. A small reinforcement formed at the weld face (Fig. 3b). The transition region of the reinforcement and HAZ was smooth and there was no undercut discovered there (Fig. 3c). Semi-elliptical band structures formed in the weld zone (Figs 3c and 3d). These bands are related to the interrupted cooling during weld pool solidification process. Owing to variations of arc heat flux and arc force inside the weld pool, the liquid metal flowed, stirred and solidified, bands were formed along the solidification front and columnar grains were forced to change the course of the growth. To evaluate the difference of inner and outer of the band, the compositions of the inner and outer band zone were evaluated by EDS and no evident differences were discovered. Moreover, the micro-hardnesses of inner and outer side of such band were similar (Fig. 6e). Two types of typical substructures, i.e., cellular substructure and willow-leave substructure, were discovered as shown in Fig. 3d. It is worth noting that some hot reheating cracks were discovered in the middle of the joint (zone D in Fig. 3a), as shown in Fig. 3e.

The base material is composed of single-phase austenite with an average grain size of 30–40 μm detected by OM (Fig. 1). It can be identified that the grain size in HAZ were different, with the change of distance to the weld pool edge as shown in Fig. 3f. At a certain distance, the longer distance to the pool edge is, the larger grain of HAZ is. In detail, when a distance to weld pool edge was 0.2 mm, the grain size was found about 220 μm. While, with the increase of distance, the grain size decreased gradually. When the distance was about 0.8 mm, the average grain size of
HAZ was similar to that of basic material (35 µm). It is worth noting that the grain coarsening at HAZ is mainly due to the heating effect during the GTAW process, which obeys Ashby-Easterling model\textsuperscript{22}.

Some under-bead cracks were discovered on the reinforcement surface of the joint as shown in Fig. 4. It has been reported that the cracks can be initiated by oxygen\textsuperscript{23}. During the multi-layer GTAW process, oxygen from air or protecting atmosphere can contact and react with the surface liquid metal. Moreover, when invar alloy reacts with oxygen at a temperature range of 600-1100°C; its ductility can be determined. Thus, a hot crack forms under the tensile stress caused by contraction distortion on the cooling process of the joint. Some oxygen diffused into the metal along the grain boundaries and segregated on the grain boundaries, resulting in crack penetrating into the weld through these grain boundaries (Fig. 4).

**Ductility dip crack of the joint**

Some cracks were discovered at the middle zone of the joint (Zones 1 and 2 of Fig. 2) as shown in Fig. 5. It is noted that the middle zones are reheated more than once during the multi-pass welding, and therefore these cracks are reheating cracks. Moreover, no liquid film can be discovered at the cracks, and hence, these cracks are not liquid hot cracking but ductility dip cracks\textsuperscript{4,13}. It can be seen that all of cracks existed at the grain boundaries (OM (Figs 5a and 5b) and SEM (Figs 5c and 5d)) in the joint. Grain boundary migration owing to the weld thermal cycle of a second pass was also discovered, shown in Fig. 5a. Meanwhile a few cracks were discovered at the grain boundaries of HAZ and these cracks originated from the weld and spread to HAZ along the grain boundaries (Fig. 5b). Because the compositions of the welding wire were much similar to invar alloy, the weld zone was similar compositions to BM. Furthermore, some elements, i.e., O, S or P probably came into the weld from air or the welding wires because a small S element existed in both invar alloy and the welding wire. It is reported that S segregating at the grain boundaries can form lower melting NiS (644°C) during the welding process and subsequent reheating process (multi-pass GTAW). However, it is undetectable in a conventional scanning electron microscopic examination due to its too low content. On the other hand, thermal tensile stress was induced during cooling process in the multi-pass

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**Fig. 3** — The microstructures of the joint (a) macro morphology of the cross-section of the sample; (b) microstructure of the weld face, (c) no undercut at the transition zone, (d) an optical micrograph shows the change in dendrite morphology from cellular to dendritic, (e) microstructure of the middle of the weld (grain boundary migration) and (f) microstructures of HAZ

**Fig. 4** — Surface cracks on the weld reinforcement

**Fig. 5** — Hot cracking at the grain boundary and HAZ (a) cracks and grain boundary migration, (b) cracks at weld and HAZ, (c) and (d) cracks of SEM
welding. Normally the lower melting compounds exist at the grain boundary. Thus the crack generates and spreads along the grain boundary. Since S is the main reason for the formation of ductility dip cracks in the reheated zone, low S content or addition of Ti, Mn and Mo elements of filler metal is beneficial to reduce the cracking potential.

Micro-hardness of the joint

The micro-hardness of five positions of invar alloy base metal was tested and the results were 142.89 Hv, 143.21 Hv, 138.78 Hv, 137.88 Hv and 140.81 Hv, respectively. The average value was 140.71 Hv. To evaluate the distribution of the micro-hardness of the joint, the micro-hardness distribution across the transversal surface of the joint along the line (shown in Fig. 6a) was measured as shown in Fig. 6b. It can be seen that the micro-hardness of the welding zone and HAZ were similar to that of base metal. The micro-hardness distribution of invar joint was much different from the result of other material joint, in which welding zone is usually harder than base metal. It should be noted that the micro-hardness of the weld zone was determined by the composition of the welding wire in GTAW joint. Since the wire compositions were much similar to the base material thus the composition and phase constituents (Fig. 7) of the welding zone were close to those of base metal. The uniform micro-hardness distribution across the joint was attained. On the other hand, micro-hardnesses of Zone A, Zone B and Zone C were also similar to that of base metal, shown in Fig. 6(c-e). The micro-hardness distribution of HAZ is shown in Fig. 6f. The result indicated that the micro-hardness cross HAZ from basic material to welding zone changed insignificantly. XRD of base metal and the joint were tested as shown in Fig. 7. XRD patterns of invar alloy and the weld zone were the same (composed of Taenite (Fe, Ni) alloy) and no obvious new phases formed in the joint during the GTAW process, which is the dominant reason for the distribution of the micro-hardness cross the joint.

Tensile properties of the joint

The tensile strength of invar alloy was about 462 MPa and its elongation was about 35% measured by a standard tensile experiment. The tensile properties of four GTAW joints were given in Table 4. The average tensile strength and elongation were 442.75 MPa and 16.25%, respectively, which reach 95.8% and 46.4% of the base metal, respectively. All
fracture position of the GTAW joints was on the weld seam. The fracture morphology of the joint is shown in Fig. 8. It can be seen that the fractograph exhibits typical ductilelike pattern and the fracture of the joint is ductile.

Conclusions

Invar alloy has been welded by gas tungsten arc welding with INVAR®M93 welding wire. The microstructures of the joint were observed by OM and SEM. The mechanical properties of the joint were evaluated by tensile strength and elongation. The following conclusions can be drawn from this study:

(i) Semi-elliptical band structures formed in the weld zone, which are related to the interrupted cooling during weld pool solidification process. The compositions and micro-hardness of inner and outer of bands are similar.

(ii) Ductility dip cracks formed at the grain boundaries of the joint and HAZ. The the cracks are related to S segregating at grain boundaries to form low melting point (NiS) and tensile residual stress during the cooling process of the welding.

(iii) Some micro cracks formed at the reinforcement surface of the joint. Oxygen plays a dominant role in the formation of these cracks.

(iv) The tensile strength and elongation of the joint reached 95.8% and 46.4% of the base metal, respectively. The fracture position was on the weld zone.

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References


Table 4 — Tensile properties of the joints

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<tr>
<td>1</td>
<td>449</td>
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<td>2</td>
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<tr>
<td>4</td>
<td>438</td>
<td>16.0</td>
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<tr>
<td>Average</td>
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Fig. 8 — Fracture morphology of the joint