Effect of Ni addition on microstructure evolution
Keyhole-GTAW WM of a duplex stainless steel

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Abstract. To improve the phase balance in the weld metal of keyhole gas tungsten arc welding (K-GTAW) joint, the Ni element was added in a form of pasting a certain width and thickness (depending on the added content) of nickel band on the I-type groove. The results show that three different convection zones along thickness direction, which are the Marangoni convection, a convection driven by Lorentz force, as well as a transition layer. And then the chemical composition (Ni element content) and solidification mode transform along thickness direction. Therefore, the lathy, acicular and Widmanstätten austenite, in turn, appear along thickness direction. Meanwhile, the intensity of Kurjdumov-Sachs (K-S) orientation relationships ORs dominants gradually.

1. Introduction
Owing to its excellent properties, duplex stainless steel (DSS) is increasingly developed and widely used in the petrochemical and chemical industries, pulp and paper industries [1-3]. The welding is an integral part in the manufacturing process. At present, the welding techniques, which are used to weld mid-thick DSS, is highly cost and high requirements for assembly quality, such as submerged arc welding (SAW) and several high-energy density beam welding techniques. The groove preparation is inevitable for the SAW.

The keyhole gas tungsten arc welding (K-GTAW) technology was proposed and invented by the Australian Research Organization Commonwealth Scientific and Industrial Research Organization (CSIRO) in 1997 [4]. With an increase in the welding current, the welding arc force and energy density are enhanced, and then the weld depth is improved. Therefore, keyhole mode welding process can be achieved with GTAW if the arc pressure is power enough to overcome the surface tension of the weld pool [5]. Mid-thick plates can hence be welded in a single pass without filler metal.

As the austenite stabilizer, Ni content in WM is higher than base metal (BM). Nevertheless, ferrite content in WM of K-GTAW is too high because of the absence of filler metal, and then the mechanical properties are deteriorated. Therefore, the aim of the paper is to further study effect of Ni addition on microstructure and hardness of WM along thickness direction.
2. Experimental procedure

2.1 Materials and Welding Procedure
An 8 mm thick 2205 DSS was used as the BM. The Table 1 and Figure 1 show chemical composition and microstructure of BM, respectively. And the A-TIG1000 welding equipment was employed. The shielding and back gas used was argon at 12 L/min. And the welding current with 530 A and the welding speed with 6 mm/s were used. The Ni element was added in a form of pasting a certain width and thickness (depending on the added content) of nickel band on the I-type groove.

Table 1 Chemical composition of BM.

| Element | C   | Si  | Mn  | Cr   | Ni  | P   | S   | Mo  | N   | Fe  |
|---------|-----|-----|-----|------|-----|-----|-----|-----|-----|-----|
| Composition (wt. %) | 0.02 | 0.30 | 0.61 | 22.81 | 5.09 | 0.025 | 0.015 | 3.21 | 0.16 | Bal |

Figure 1. Microstructure of BM.

To obtain more austenite content, ER2209 (Ni content is about 9%) is used as the filler metal in 2205 DSS WM. Thus, in the present paper, the WM with 9 wt.% Ni element was used. The cross sectional area of nickel band required was calculated according to that of WM without nickel band. The evaluated equation is followed as:

\[
\text{Ni\%} = \frac{5.09\%S_0 + 99.99\%S_{\text{nickel}}}{S} = S_0 + S_{\text{nickel}}
\]

where, \(S_0\) is the cross sectional area of WM without nickel band, \(S_{\text{nickel}}\) is the cross sectional area of nickel band, \(S\) is the cross sectional area of WM with nickel band.

2.2 Microstructure Characterization and hardness test
The microstructure DSS welded joints was etched using a 30% KOH electrolyte and carefully observed through an optical microscope (OM) and scanning electron microscope (SEM, EOL JSM-7200F) with EDS (OXFORD X-Max50). The phase ratio was measured by manual point counting method according to ASTM E 562. And the electron backscatter diffraction (EBSD, OXFORD Nordlys MAX3) test performed to investigate the orientation of WM. The applied load of 1 kgf was used to measure the hardness of both BM and WM. The dwell time was 15 s.

3. Results and discussion

3.1 Molten pool flow behavior
Figure 2 shows the cross section of penetrated joint. There are three different colored zones along thickness direction, which are the Marangoni convection (I), a convection driven by Lorentz force (III),
and a transition layer (II). Kou et al. [6] indicated that both the molten pool flow velocity by surface tension and Lorentz force are higher than that by the welding speed. In the case that the convection is ignored, the chemical composition of the molten pool would be uniform. However, the real case is that the two convective modes are relatively closed [6]. This results in less flow of chemical composition between the two convective modes. As a result, the Ni content is different along thickness direction, and then the microstructure types transform. And in the present paper, WM is divided into three parts, i.e. WM_{MC} (WM in the Marangoni convection), WM_{TL} (WM in the transition layer), WM_{LF} (WM in the convection driven by Lorentz force).

Figure 2. Cross section of penetrated joint.

3.2 Microstructure characterization
Figure 3 shows the microstructure of WM along thickness direction. The ferrite and austenite morphologies are different along thickness direction, which is attributed to the different solidification mode induced by various Ni content. And the ferrite morphology transforms from fine lath to discrete lump along thickness direction, which indicates that ferritic-austenitic solidification mode transforms.

Figure 4 shows different elements mapping in WM_{LF}. The elemental partitioning between austenite and ferrite is greater in DSS. And the ferrite phase significantly enriches in Cr and Mo element, but has less Ni element. Westin et al. [7] showed that the segregation of metallic elements could be induced by the dendritic solidification structure. It is well-known that the ferritic solidification mode in DSS welds displays a feature of dendrite growth from the fusion boundary, which could be regulated by the thermal gradient [8]. Meanwhile, the dendritic solidification structure could result in particular segregation of metallic elements [9]. And then the phase transformation mode is diverse owing to the various segregation degree. It is marketable that a Fe-depleted, Cr-depleted, Ni-depleted but O-enriched zone occurs in the WM_{LF}. It is deduced that the presence of oxide inclusion could be due to the insufficient back shielding gas. And it would deteriorate the toughness and pitting resistance of materials.

Figure 3. Microstructure of WM along thickness direction. (a) WM_{MC}, (b) WM_{MC}/WM_{TL}, (c) WM_{TL}, (d) WM_{TL}/WM_{LF}, (e) WM_{LF}, (f) WM/HAZ
Figure 4. Different elements mapping in WM\textsubscript{LF}. (a) electron image, (b) Cr element mapping, (c) Mo element mapping, (d) Ni element mapping, (e) Fe element mapping, (f) O element mapping.

Figure 5 show the austenite content in WM\textsubscript{MC}, WM\textsubscript{TL}, and WM\textsubscript{LF}. The austenite content of all different microzones in WM is higher than that of BM. The austenite content both in WM\textsubscript{MC} and WM\textsubscript{TL} exceeds 70% of the standard requirement. This case is because of the heterogeneous distribution of Ni element in WM.

3.3 Orientation and distribution of ferrite and austenite

Figure 6 and Figure 7 show both the phase and orientation maps of the ferrite and austenite grains in WM\textsubscript{MC} and WM\textsubscript{LF}, respectively. The banded structure of both ferrite and austenite in WM disappears completely. The austenite grain parallel to the dendrite growth direction in WM\textsubscript{MC} has one similar orientation throughout the same grain. And the orientation of fine lathy ferrite presents the similar characterization. However, there are no special orientation relationships boundaries (ORs). The Widmanstätten type austenite characteristic of a ferritic solidification presents in WM\textsubscript{LF}. The ferrite matrix displays one similar orientation throughout the grain, however, the austenite consists of a number of families of austenite grains with different orientations.

In general, most of the austenite in DSS is near either the Nishiyama-Wasserman (N-W) or Kurjdumov-Sachs (K-S) ORs with adjacent ferrite [10]. In the present paper, any match within 2° deviation from the ideal ORs is classified as either N-W or K-S and all others as random grain boundaries (other ORs). Figure 8 shows the frequency of both special and other ORs. Along thickness direction, the frequency of K-W and N-W ORs increases, while that of other ORs decreases. This is because of that the variation of Ni content along thickness direction leads to the transformation modes from ferritic-austenitic solidification to ferritic solidification. Besides, the morphology of austenite transforms to the Widmanstätten type in WM\textsubscript{LF}. Aronson et al. [11] revealed that Widmanstätten type austenite transformed with a shear-assisted diffusional mode in a form of K-S ORs.
Figure 6. The EBSD images of the WMMC. (a) phase map presenting the ferrite in blue and austenite in red, (b) Euler map showing the orientation of the ferrite and austenite grains, (c) IPF of the ferrite and austenite in the RD, (d) IPF of the ferrite and austenite in the ND, (e) IPF of the ferrite and austenite in the TD.

Figure 7. The EBSD images of the WMLF. (a) phase map presenting the ferrite in blue and austenite in red, (b) Euler map showing the orientation of the ferrite and austenite grains, (c) IPF of the ferrite and austenite in the RD, (d) IPF of the ferrite and austenite in the ND, (e) IPF of the ferrite and austenite in the TD.

Figure 8. Frequency of special and other ORs.
4. Conclusions

1. Three different convection microzones along thickness direction present, which are the Marangoni convection, a convection driven by Lorentz force, and a transition layer.

2. The ferrite morphology transforms from fine lath to discrete lump along thickness direction owing to the different solidification mode induced by various Ni content.

3. Microstructure of WM in a convection driven by Lorentz force presents ~41.14% of K-S ORs because the Widmanstätten type austenite content increases.

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