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The study of nitrogen in argon gas on the angular distortion of austenitic stainless steel weldments

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Abstract

The objective of this study was to investigate the effect of nitrogen added in argon shielding gas on the angular distortion of austenitic stainless steels. An autogenous gas tungsten arc welding was conducted on austenitic stainless steels 304 and 310 to produce a bead-on-plate weld. The delta-ferrite content of welds was measured by using Ferritscope. The angular distortion of weldments was determined by using the mean vertical displacement method (MVDM). The present results indicate that the retained ferrite content in Type 304 stainless steel weld metals was rapidly reduced as the nitrogen addition in argon shielding gas was increased. The welding angular distortion was raised with the increase of the amount of nitrogen added in the shielding gas. This experimental result also found that the existence of retained ferrite microstructure within the austenitic matrix has a beneficial effect in reducing welding distortion tendency of austenitic stainless steel weldment.

Keywords: Angular distortion; Nitrogen content; Retained ferrite

1. Introduction

During welding processes, the weldment is locally heated by the welding arc and the temperature distributions in the weldment are not uniform. The welding temperatures are also changed along with welding times. Typically, the weld metal and base metal immediately adjacent to the fusion zone are at a temperature substantially above that of the unaffected base metal. During the welding cycle, nonuniform thermal strains are induced in both the weld metal and base metal near the fusion zone. The thermal strains produced during heating are accompanied by plastic upsetting. The nonuniform thermal stresses resulting from these strains combine and react to produce internal forces that cause welding distortion. The four basic types of welding distortion can be demonstrated for a rectangular plate with single-side centric weld as shown in Fig. 1, [1]. It was found that the welding distortions can affect the fabrication, precision (the shape and dimensional tolerances required), and function (such as reliability and stability) in finished structures.

It is well known that nitrogen dissolves interstitially in austenite and is a strong austenite stabilizer. The stabilizing effect of nitrogen is 20–30 times that of nickel [2–4], therefore, a nitrogen element has been added into austenitic stainless steels to substitute for nickel element as an austenite stabilizer. Nitrogen addition to the shielding gas is used for certain alloys in practice with arc welding. However, from the viewpoint of welding techniques, adding nitrogen gas to the shielding gas while maintaining strict control of the nitrogen content in the weld metal is quite difficult. With GTA welding, electrode erosion resulted in excessive spatters and arc instability [5].

It has been known that nitrogen has an positive effect on the increase of mechanical strength (such as ultimate tensile strength, yield strength, creep strength, and impact strength etc.) [5–10], improvement of pitting corrosion resistance [6,11], and so on. However, the study of the influence of nitrogen on the angular distortion of weldments is limited. This paper is aimed at detailed experiments to determine the effect of nitrogen gas when added to argon shielding gas with GTA welding on the retained ferrite content and angular distortion of austenitic stainless steels.

2. Experimental procedure

Types 304 and 310 stainless steels were used in this study. Their chemical compositions and mechanical properties are presented in Tables 1 and 2. The 8 mm austenitic stainless steel plates were cut into strips of size 130 mm × 130 mm.

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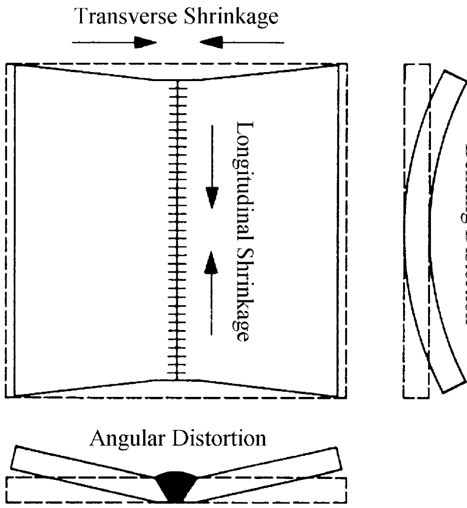


Fig. 1. The basic type of welding distortion for the rectangular plate with single-side centric weld.

Table 1
Chemical composition (wt.%) of austenitic stainless steels

Material	C[a]	Si	Mn	P[a]	S[a]	Cr	Ni	Fe
Type 304	0.08	0.44	0.95	0.04	0.04	18.7	8.16	Balance
Type 310	0.20	0.79	1.64	0.04	0.04	23.9	19.61	Balance

[a] Maximum value.

The strips were roughly polished with 400 grit abrasive paper to remove surface impurities, then cleaned with acetone. An autogenous gas tungsten arc welding was conducted with a standard 2% thoriated tungsten electrode. The electrode tip configuration was a blunt point with a 90° included angle. The welding processes were performed under the pure Ar gas, Ar + 2.5% N_2, Ar + 5% N_2, Ar + 7.5% N_2, Ar + 10% N_2, and Ar + 15% N_2 mixed gases. These shielding gases were flowing at 20 l/min.

In order to record the thermal cycle of weldment during GTA welding process, a thermocouple was attached at 2 mm from the fusion line of welds. The thermal cycle of recording equipment included the dynamic temperature measurement system and a chromel–alumel thermocouple and is shown in Fig. 2.

Table 2
Mechanical properties of austenitic stainless steels

‘	Yield strength (MPa)	Elasticity modulus (GPa)	Poisson's ratio
Type 304	290	193	0.25
Type 310	311	204	0.32

The mean vertical displacement method (MVDM) was used to measure the welding distortion. A schematic illustration of the MVDM is presented in Fig. 3(a). A position-fixed hole is drilled at the back of P_1, P_2, and P_3, and a pillar is attached to each hole. Three pillars (one is a stable pillar and the other two are adjustable pillars) were used to adjust the horizontal level. The distance from each point to the horizontal surface was recorded. Measurements were taken both before and after welding. The difference between the measurements before and after welding gave the vertical displacement caused by welding, and the value of angular distortion can be derived from this mean vertical displacement (U):

$$|U| = \frac{1}{2}((A + B) - (C + D))$$

where A, B, C and D are the mean vertical displacement values of each point as shown in Fig. 3(b).

The ferrite number (FN) was measured by using a calibrating magnetic instrument with Ferritscope M10B-FE. In order to minimize the measured errors due to weldment inhomogeneity, the average value of seven measurements from different locations along the as-welded surface was recorded.

The nitrogen contents in austenitic stainless steel weld metals were analyzed by using the equipment with Leco

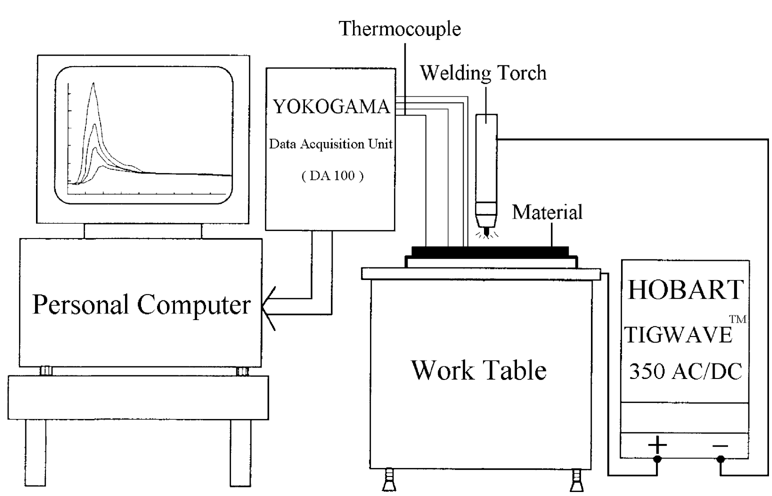


Fig. 2. Thermal cycle recording system used.

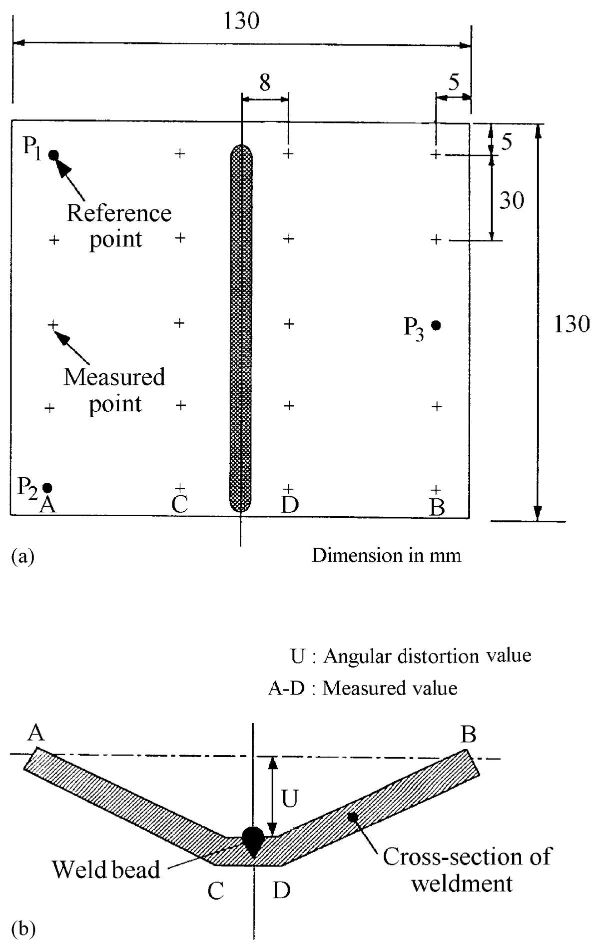


Fig. 3. Schematic illustration of the MVDM.

TC-436. Vickers hardness test was used to examine the metallurgical properties of austenitic stainless steel weld metals. All metallographic specimens were prepared by mechanical lapping, grinding, and polishing to a 0.3 μm finish, followed by etching in a solution of 10 g $CuSO_4$ + 50 ml HCl + 50 ml H_2O.

3. Results and discussion

The welding parameters used in this study are presented in Table 3. The welding current, travel speed, and gas flow rate were all fixed with varying volume percent nitrogen gas added in argon shielding gas during GTA welding process.

3.1. Effect of nitrogen added in argon shielding gas on heat input

Fig. 4 shows the calculated heat input per unit length in a weld with various amount of nitrogen added in argon shielding gas with GTA welding. As the nitrogen added in argon shielding gas increases, the magnitude of the amount of heat input is increased. The result can be related to the measured thermal cycle of weldment during GTA welding process as shown in Fig. 5. As the magnitude of the nitrogen added in argon shielding gas increases, the peak temperature of thermal cycle in the weldment is increased. This is consistent with the results of investigations by Lin et al. [12–14].

The effect of nitrogen addition in argon shielding gas on the arc voltage is presented in Table 3. The welding current and travel speed were kept a constant value, it was shown that the arc voltage increases as nitrogen added in argon shielding gas increases. Since the calculated heat input is proportional to the measured arc voltage, added nitrogen has a positive effect on the increasing of heat input with welding fabrication.

3.2. Effect of nitrogen added in argon shielding gas on nitrogen contents in weld metals

The experimental results of analyzed nitrogen content of welds in Types 304 and 310 stainless steels are presented in Fig. 6. The amount of nitrogen content in weld metals increases considerably with the increase of nitrogen added in argon shielding gas up to 15 vol.% nitrogen gas added in the shielding gas. The nitrogen content becomes saturated around 0.51 wt.% in Type 310 stainless steel weld metals.

Table 3
Welding parameters for autogenous GTA welding

Material	Current (A)	Voltage (V)	Travel speed (cm/min)	Flow rate (l/min)	Shielding gas
Type 304	150	16.3	15	20	Pure Ar
Type 304	150	17.0	15	20	Ar + 2.5% N_2
Type 304	150	17.6	15	20	Ar + 5.0% N_2
Type 304	150	18.1	15	20	Ar + 7.5% N_2
Type 304	150	18.8	15	20	Ar + 10% N_2
Type 304	150	19.7	15	20	Ar + 15% N_2
Type 310	150	16.8	15	20	Pure Ar
Type 310	150	17.4	15	20	Ar + 2.5% N_2
Type 310	150	18.0	15	20	Ar + 5.0% N_2
Type 310	150	18.9	15	20	Ar + 7.5% N_2
Type 310	150	19.4	15	20	Ar + 10% N_2
Type 310	150	20.5	15	20	Ar + 15% N_2

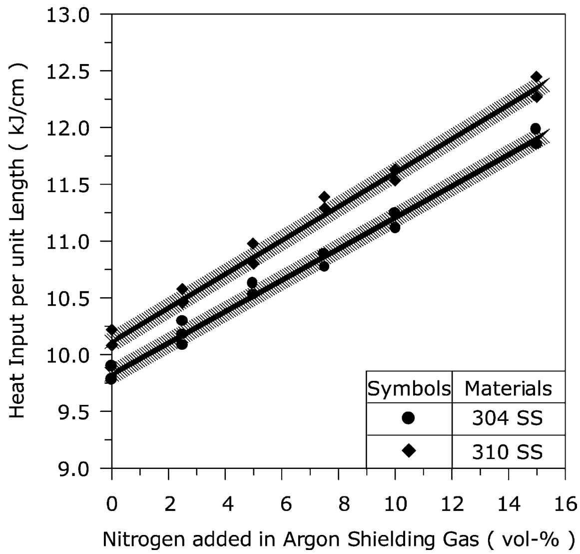


Fig. 4. Calculated heat input as a function of nitrogen added in argon shielding gas with GTA welding.

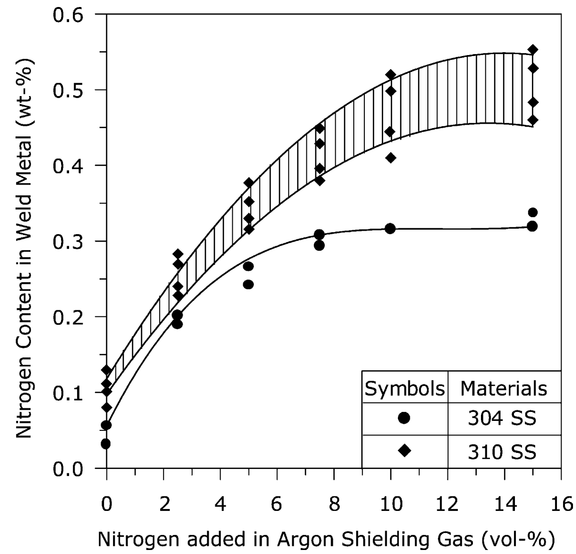


Fig. 6. Analyzed nitrogen content of GTA weld metal as a function of nitrogen added in argon shielding gas.

In Type 304 stainless steel weld metals, the nitrogen content in welds was increased with the increase of nitrogen added in argon shielding gas up to 7.5 vol.%, beyond which the nitrogen content in weld metals assumes a constant value of around 0.31 wt.%. In other words, the maximum nitrogen solubility in Type 304 stainless steel weld metals is approximately 0.31 wt.%.

It has been reported that the nitrogen solubility in weld metal is mainly determined by the heat input and arc length with GTA welding [5,15]. In this study, since the arc length was kept constant, therefore the nitrogen solubility in the weld metal was determined only by the heat input. As the nitrogen added in argon shielding gas increases, the arc voltage is increased. The amount of heat input is therefore increased. Because the higher heat input can increase the peak temperature of weld metal and reduce the cooling rate of weld metal, the amount of nitrogen present in a weld is increased.

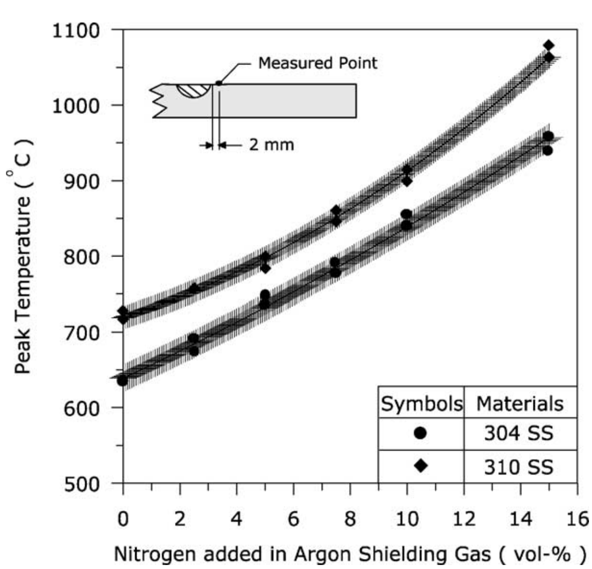


Fig. 5. Effect of the nitrogen added in argon shielding gas on the peak temperature in weldment at 2 mm from the fusion line.

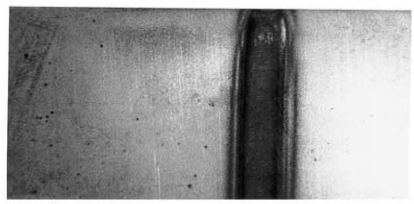
The above results clearly indicate that Type 310 stainless steel welds can absorb more nitrogen than Type 304 stainless steel welds under the same welding conditions. This result can be analyzed from the chemical composition of the materials used. As shown in Table 1, the amount of chromium in Type 310 stainless steel is greater than that of Type 304 stainless steel. According to the study by Lancaster [16], the nitrogen solubility increases with increasing chromium content of the materials used. For this reason, the limit of nitrogen solubility in Type 310 stainless steel welds is greater than that of Type 304 stainless steel welds when the same volume percentage of nitrogen gas is added in the shielding gas.

There is generally an increase in the nitrogen content in weld metals as nitrogen is added in argon shielding gas. The weld discontinuity such as porosity can occur when the nitrogen content in weld metal is increased to near the solubility limit. Fig. 7 shows the as-welded surface appearances of bead-on-plate GTA welding on Types 304 and 310 stainless steels, with using an Ar + 10% N_2 shielding gas mixture. Extensive porosity can be seen on the as-welded surface of Type 304 stainless steel, but there is no sign of such an occurrence with Type 310 stainless steel that has a relatively greater solubility of the nitrogen content in weld metal.

3.3. Effect of nitrogen content in weld metal on retained ferrite content

The measured FN as a function of nitrogen content in weld metal is presented in Fig. 8. A rapid drop of measured FN can be shown in weld metals as the nitrogen content is

(a) Type 304 stainless steel as-welded surface
(with Ar + 10% N_2 shielding gas mixture at 150 A and 15 cm/min)



(b) Type 310 stainless steel as-welded surface
(with Ar + 10% N_2 shielding gas mixture at 150 A and 15 cm/min)

Fig. 7. Effect of nitrogen on porosity in as-welded surface made with GTA welding.

increased. In Type 304 stainless steel welds the FN is reduced to 1.7 FN from initial value of 7.5 FN by the addition of 0.201 wt.% nitrogen content in weld metal. With 0.308 wt.% nitrogen content in weld metal, the retained delta-ferrite content in Type 304 stainless steel welds can be reduced to near zero. Since nitrogen dissolves interstitially in austenite and is a strong austenite stabilizer, the addition of very small amounts of nitrogen in weld metal can rapidly reduce the retained delta-ferrite content in Type 304 stainless steel welds.

Because the microstructure of Type 310 stainless steel weld metal is fully austenitic at room temperature after solidification, the ferrite content does not change (FN is 0) as the nitrogen addition in argon shielding gas is increased as shown in Fig. 8.

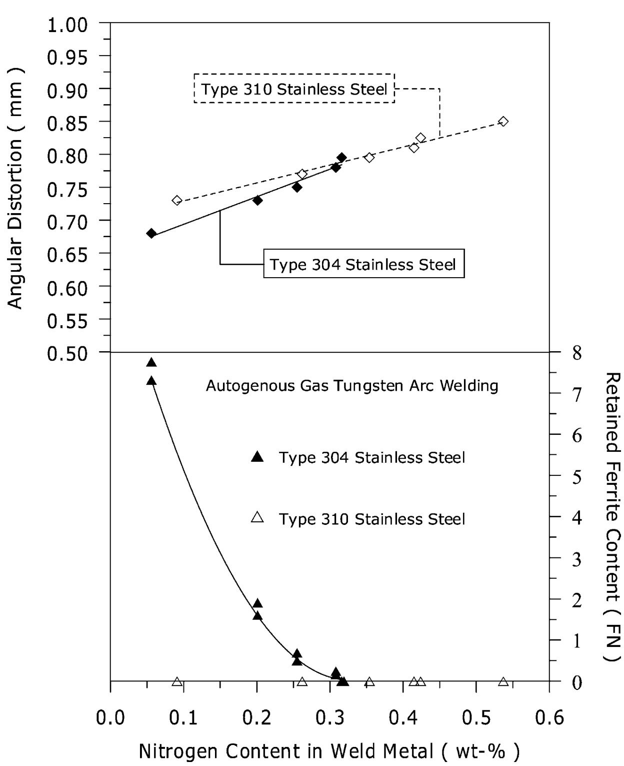


Fig. 8. Effect of nitrogen content in weld metal on retained ferrite content and angular distortion of austenitic stainless steels.

3.4. Effect of nitrogen content in weld metal on angular distortion

Fig. 8 also presents the angular distortion in austenitic stainless steel weldments measured as a function of nitrogen content in weld metal made with GTA welding. The result indicates that as the amount of nitrogen addition in the weld metal increases, the magnitude of welding angular distortion of austenitic stainless steels is increased. Based on the studies by Masubuchi [17], welding thermal stress increases with the increase of the amount of heat input. Since the nitrogen added in argon shielding gas increases, the amount of heat input per unit length in a weld can be increased. Therefore, a larger angular distortion of austenitic stainless steel weldments can be obtained by the addition of more nitrogen contents in GTA weld metals.

3.5. The effect of delta-ferrite structures on angular distortion

The effect of nitrogen content in weld metal on retained ferrite content and angular distortion of austenitic stainless steels is shown in Fig. 8. The angular distortion of both Types 304 and 310 stainless steel weldments are closed under the same nitrogen content, as the retained ferrite content is reduced to near zero FN in Type 304 stainless steel welds. However, with lower nitrogen content, the delta-ferrite contained Type 304 stainless steels have smaller angular distortion than that of Type 310 stainless steels with the same nitrogen content. The existence of delta-ferrite structures within the austenitic matrix may affect the angular distortion tendency in stainless steels and can be proposed as following.

The first explanation is based on the fact that the delta-ferrite structure has a greater high temperature ductility than that of austenite structure. Therefore, the delta-ferrite within the austenitic matrix can moderate the action of thermal stress during welding processes.

The second explanation can be related to the fact that welding distortion is reduced because the BCC ferrite structure has a smaller coefficient of thermal expansion than that of the FCC austenite structure, therefore the shrinkage stresses during the cooling process can be decreased.

Based on the above discussion, it can be seen that the existence of retained delta-ferrite structures within the austenitic matrix has a beneficial effect in reducing welding distortion tendency in austenitic stainless steels.

3.6. Effect of nitrogen added in argon shielding gas on Vickers hardness of austenitic stainless steel weld metals

Fig. 9 shows the Vickers hardness of austenitic stainless steel weld metals measured with various percents by volume of nitrogen gas added in the shielding gas during GTA welding process. The experimental result indicates that the hardness of austenitic stainless steel welds increases as the nitrogen added in argon shielding gas increases. The interstitial solid solution strengthening and precipitation hardening are probably the causes of the increase of the hardness in austenitic stainless steel weld metals [5–10,18].

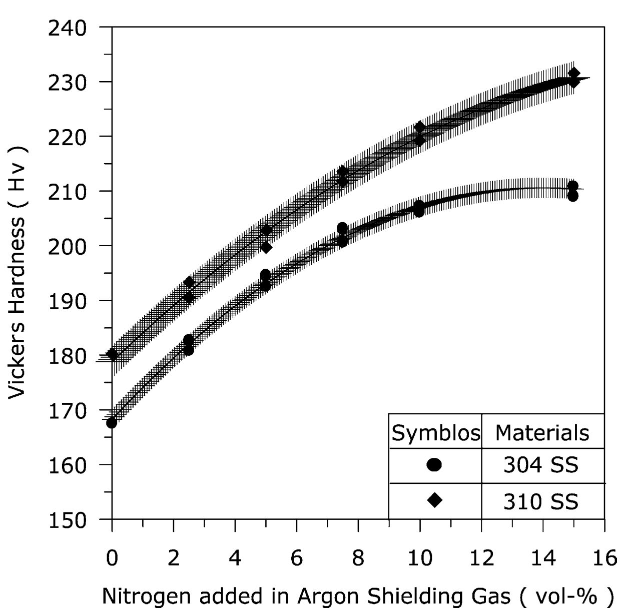


Fig. 9. Measured hardness of GTA weld metal as a function of nitrogen added in argon shielding gas.

Fig. 9 also indicates that the hardness of Type 310 stainless steel weld metal is higher than that of Type 304 stainless steel with the same percentage by volume nitrogen gas added in the shielding gas. This can be related to the fact that Type 310 stainless steel welds can absorb more nitrogen than that of Type 304 stainless steel under the same GTA welding conditions.

4. Conclusions

1. Nitrogen addition in argon shielding gas made with GTA welding can increase the amount of heat input.
2. The nitrogen content in austenitic stainless steel weld metals can be increased with the increase of nitrogen added in argon shielding gas.
3. Adding nitrogen in the weld metal is an economical and effective way to reduce the retained ferrite content in Type 304 stainless steel welds.
4. Welding angular distortion increases with the increase of nitrogen content in weld metal made with GTA welding.
5. The existence of retained delta-ferrite microstructures within the austenitic matrix has a beneficial effect in reducing the welding distortion tendency of austenitic stainless steels.
6. The hardness of austenitic stainless steel welds increases with the increase of the nitrogen content in the weld metal.

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