

Nitrogen Control during Autogenous Arc Welding of Stainless Steel — Part 1: Experimental Observations

The influence of shielding gas nitrogen content and base metal nitrogen and sulphur concentrations on nitrogen absorption/desorption was investigated

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ABSTRACT. This study deals with nitrogen absorption and desorption during the autogenous welding of stainless steel, investigating the influence of the base metal nitrogen and surface-active element concentrations and nitrogen partial pressure in the shielding gas. The weld nitrogen concentration increases with shielding gas nitrogen content at low nitrogen partial pressures, but at higher partial pressures, nitrogen absorption is balanced by N₂ evolution. This steady-state nitrogen content is not influenced significantly by the base metal nitrogen content in low-sulphur alloys, but in high-sulphur alloys, an increase in the initial nitrogen concentration causes higher weld nitrogen contents over the entire range of partial pressures evaluated. The weld metal saturation limit is reached at progressively lower shielding gas nitrogen contents as the base metal nitrogen level increases. It is postulated that less nitrogen is required in the shielding gas to reach the saturation limit in the high-sulphur alloys because an appreciable fraction of the nitrogen already present in the base metal is prevented from escaping by a higher level of surface coverage.

Introduction

In mild steel, low-alloy steel, and ferritic stainless steel, nitrogen is generally considered an undesirable impurity, causing porosity and the formation of brittle nitrides (Ref. 1). In austenitic and duplex austenitic-ferritic stainless steels, however, nitrogen is often a valued alloying element. In part, this has stemmed from the desire to use nitrogen as a substitute for nickel, thereby reducing alloying element costs. In addition to the fact that the consumption of an expensive strategic metal is reduced, nitrogen is considered to be as much as thirty times as powerful as nickel as an austenite-former (Refs. 2, 3). Nitro-

gen is also an excellent solid solution strengthening element in stainless steel, increasing the yield strength at room temperature and at subzero temperatures (Refs. 4, 5) with no significant decrease in toughness or ductility (Refs. 5, 6). Nitrogen-alloyed austenitic stainless steels, therefore, offer a unique combination of strength and toughness. Nitrogen is also reported to improve the passivation characteristics of stainless steels. It increases resistance to localized corrosion (Refs. 7, 8) and reduces sensitization effects during welding (Refs. 9, 10).

In order to realize the advantages associated with nitrogen alloying, the nitrogen has to be in solution in the metal matrix. Excess nitrogen tends to cause porosity or form brittle nitrides. Iron, mild steel, and low-alloy steel have low solubility limits for nitrogen (the equilibrium solubility of nitrogen in iron at its melting point is only approximately 0.044 wt-% at 1 atm — Ref. 11). It is therefore important to limit nitrogen contamination in these steels. This poses a particular problem during welding, where nitrogen from the surrounding atmosphere can be absorbed by the weld metal in spite of the precautions normally taken to shield the arc and the weld pool from the surroundings by using slag and/or shielding gas. Without the benefits of effective shielding, nitrogen contents as high as 0.2% have been reported in steel welds after arc welding (Ref. 11). These concentration levels are far greater than those in the base and filler metals and indicate the importance of the dissolution of nitrogen into the molten metal from the arc atmosphere during welding.

Austenitic stainless steels can accommodate significantly higher levels of nitrogen in solution. In nitrogen-alloyed austenitic stainless steels, the most important problem during welding is often not nitrogen absorption but nitrogen desorption to the arc atmosphere, resulting in lower nitrogen levels in the weld metal. A decrease in nitrogen concentration in the region of the weld has a detrimental effect on the mechanical properties and corrosion resistance of the joint.

In order to control nitrogen absorption and evolution from the molten pool during welding, a fundamental knowledge of the absorption and desorption mechanisms is essential. Over the past years a number of studies have dealt with arc melting experiments under static conditions (stationary arc), and other studies concerned experiments under more realistic welding conditions (traveling arc). The results of these studies show that nitrogen absorption and desorption are complex phenomena, influenced by many factors. Some of these investigations are considered below.

The equilibrium solubility of nitrogen in iron is governed by Sievert's law, which states that the nitrogen concentration in liquid iron is proportional to the square root of the nitrogen partial pressure above the melt — Equation 1 (Ref. 11).

$$\underline{N}_{eq} = K_{eq} \sqrt{P_{N_2}} \quad (1)$$

where \underline{N}_{eq} is the nitrogen concentration in liquid iron at equilibrium with diatomic nitrogen (wt-%), K_{eq} is the equilibrium constant for reaction (1), and P_{N_2} is the partial pressure of N₂ in the atmosphere (atm).

Sievert's law implies that the nitrogen solubility limit in iron alloys can be raised by increasing the partial pressure of the diatomic gas above the melt. This approach has been proposed for reducing nitrogen losses and for preventing nitrogen-induced porosity during the welding of nitrogen-containing austenitic stainless steels. The majority of researchers, however, agree that Sievert's law cannot be applied to describe the dissolution of a diatomic gas in liquid metal in the presence

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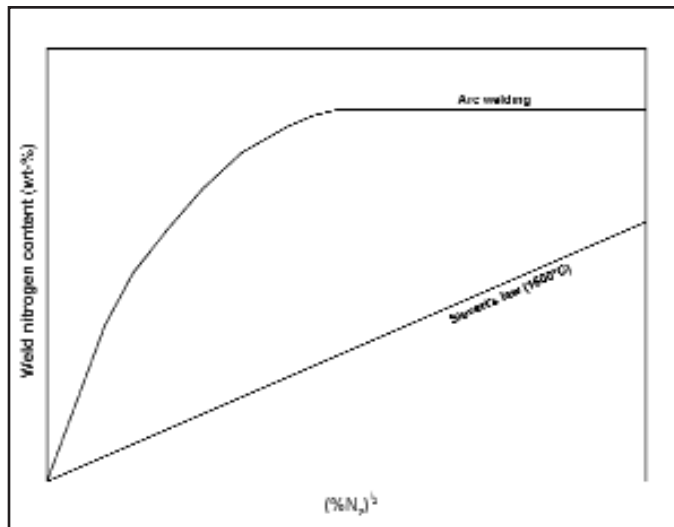


Fig. 1 — Schematic illustration of the weld metal nitrogen concentration as a function of the square root of the nitrogen partial pressure in the shielding gas.

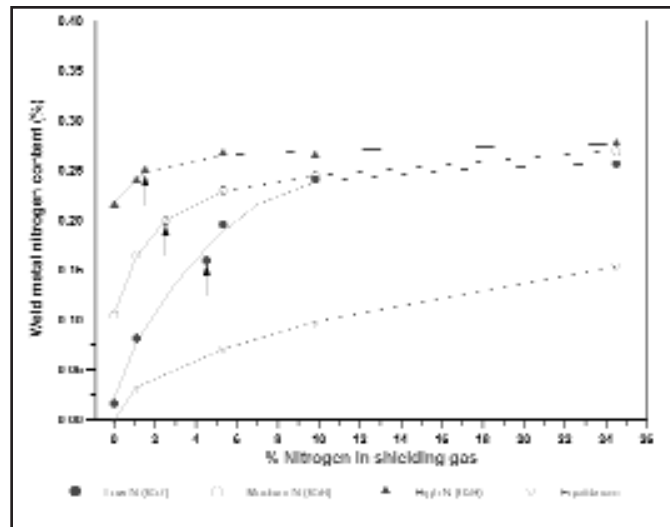


Fig. 2 — Weld metal nitrogen concentration as a function of the shielding gas nitrogen content for the experimental low-sulphur alloys. The arrows indicate the minimum shielding gas compositions where bubbling was observed experimentally.

of a plasma (Refs. 12–16). Such a plasma phase resides above the weld pool during most fusion welding processes. Reported weld nitrogen contents generally exceed the concentrations predicted from equilibrium considerations. As shown schematically in Fig. 1, the weld nitrogen content is reported to increase with an increase in P_{N_2} at low partial pressures. At higher shielding gas nitrogen contents, the weld nitrogen concentration assumes a constant steady-state value that is independent of the actual partial pressure. At this point a dynamic balance is established and the rate of nitrogen absorption at the weld surface is balanced by bubble formation in the melt.

The majority of authors attribute the enhanced solubility in the presence of a plasma to the existence of monatomic nitrogen, N, in the arc (Refs. 16–19). These nitrogen atoms form as diatomic nitrogen molecules partially dissociate in the high-temperature arc.

Gedeon and Eagar (Refs. 18, 19) proposed a two-step absorption process in which hydrogen (also a diatomic molecule) dissociates in the high-temperature regions of the arc, followed by absorption at the weld pool surface. Their thermodynamic model was subsequently modified by Mundra and DebRoy (Ref. 20) and Palmer and DebRoy (Ref. 21) to describe the dissolution of nitrogen in welds. The authors defined a hypothetical dissociation temperature, T_d , at which the equilibrium dissociation of diatomic nitrogen produces the actual partial pressure of monatomic nitrogen present in the plasma. The monatomic nitrogen in the arc plasma then dissolves in the weld

metal at the weld pool surface temperature, T_s .

This model does not take into account the weld composition, which has a significant effect on the solubility of nitrogen in iron (Refs. 22, 23). Kuwana et al. (Ref. 24) addressed this in the form of a thermodynamic model developed to predict nitrogen solubilities in stainless steel welds during autogenous welding. The authors reported that the weld nitrogen content is a function of the chromium content of the base metal. Chromium appears to increase the equilibrium nitrogen solubility and the time required to reach this equilibrium value. In low-chromium alloys, the weld nitrogen concentration approaches the equilibrium solubility, but enough time may not be available during welding for nitrogen absorption to increase the weld nitrogen content to a level approaching the equilibrium value in high-chromium steels.

These results suggest that a kinetic approach may be more appropriate for describing the dissolution of nitrogen in stainless steels. Katz and King (Ref. 16) studied nitrogen absorption and desorption kinetics during the arc melting of iron and observed both first- and second-order kinetics, depending on the composition of the alloy, and, in particular, the surface-active element concentration of the alloy. Alloys containing high levels of surface-active elements displayed second-order desorption kinetics, whereas alloys with low concentrations of these elements displayed first-order kinetics. The Katz and King kinetic model, however, does not address the influence of alloying elements or welding parameters.

Nitrogen absorption and desorption during the autogenous welding of nitrogen-alloyed stainless steels is expected to be a function of the base metal nitrogen content prior to welding and the weld surface-active element concentration. Limited information is available describing the influence of the base metal nitrogen content on nitrogen dissolution in iron alloy welds. Okagawa et al. (Ref. 6) and Suutala (Ref. 25) studied autogenous gas tungsten arc welds in a number of austenitic stainless steels with nitrogen levels varying between 0.008 and 0.076% and concluded that base metal nitrogen does not take part in the nitrogen dissolution reaction during welding. Arata et al. (Ref. 26) reported that the total weld nitrogen content is the sum of the residual nitrogen content of the base metal and any nitrogen picked up from the shielding gas. The nitrogen levels of the steels investigated by these authors were relatively low compared to those of nitrogen-alloyed austenitic stainless steels, and were probably well below the nitrogen solubility limit of the weld metal. For this reason, it is unlikely that their conclusions can be extended to the case of high-nitrogen alloys.

Ample evidence exists to show that the presence of surface-active elements, in particular sulphur and oxygen, has a significant influence on nitrogen dissolution in iron alloy welds. Lancaster (Ref. 1) reported that the amount of nitrogen absorbed during arc welding increases in the presence of oxygen, and Ogawa et al. (Ref. 27) demonstrated that nitrogen-induced porosity in austenitic stainless steel welds can be curbed by welding in an atmosphere containing a small amount of ox-

dizing gas. According to Blake (Ref. 11), the presence of oxygen leads to lower nitrogen desorption rates, and Uda and Ohno (Ref. 28) reported that the presence of surface-active elements markedly increases the nitrogen content of iron and the level of supersaturation in welds. Sinha and Gupta (Ref. 29) observed that the nitrogen absorption rate in stainless steel decreases in the presence of surface-active elements. The most likely explanation for the influence of surface-active elements is that these elements occupy a fraction of the available surface sites, making it more difficult for nitrogen to adsorb on or desorb from the metal surface (Ref. 16).

Objectives of the Investigation

As demonstrated above, the absorption and desorption of nitrogen during welding are complex phenomena influenced by many factors, including the nature of the species present in the arc plasma, the weld metal alloying content, and the welding parameters. No unified theory for the quantitative understanding of the extent of enhanced dissolution in stainless steels has emerged up to this point. Most of the theoretical models currently available in literature describe nitrogen absorption and desorption from autogenous iron or carbon steel welds and may not be appropriate for describing these processes in more highly alloyed stainless steel welds.

This investigation aimed at examining the influence of the following factors on the absorption and desorption of nitrogen during the autogenous welding of stainless steel:

- the shielding gas composition,
- the base metal nitrogen content prior to welding, and
- the surface-active element concentration in the weld metal.

These variables were selected to quantify the role of certain factors not addressed in currently available literature, to clarify inconsistencies in the existing literature, and to investigate the interaction between these variables in practice.

In order to examine the influence of each of these factors on the nitrogen content of stainless steel welds, the compositions of the base metal and the shielding gas were adjusted to produce an experimental matrix quantifying the influence of each variable individually and in combination. The same welding parameters (welding current, arc length, travel speed, and shielding gas flow rate) were used during all the experiments, except where otherwise indicated, to avoid the introduction of too many variables. Following the experimental work, a kinetic model was de-

Table 1 — Chemical Compositions of the Stainless Steel Alloys Investigated (Percentage by Mass, Balance Iron)

| Alloy | Comments | Cr | Ni | Mn | Si | C | S | N |
|---------|------------------|------|------|------|------|-------|-------|-------|
| VFA 657 | Low N, Low S | 24.4 | 20.1 | 1.91 | 1.60 | 0.075 | 0.023 | 0.005 |
| VFA 658 | Medium N, Low S | 24.6 | 19.9 | 1.89 | 1.63 | 0.080 | 0.023 | 0.105 |
| VFA 659 | High N, Low S | 24.3 | 19.9 | 1.93 | 1.63 | 0.085 | 0.022 | 0.240 |
| VFA 752 | Low N, High S | 24.6 | 19.5 | 1.99 | 1.51 | 0.087 | 0.052 | 0.006 |
| VFA 753 | Medium N, High S | 24.5 | 19.3 | 1.89 | 1.61 | 0.082 | 0.061 | 0.097 |
| VFA 755 | High N, High S | 24.5 | 19.3 | 1.90 | 1.55 | 0.079 | 0.049 | 0.280 |

rived to explain the results obtained and to serve as a basis for further modeling work. This model is described in Part 2 of this study and is considered in a separate publication.

Experimental Procedure

Stainless Steel Alloys Studied

During the course of this investigation, the influence of autogenous welding on the nitrogen content of six experimental stainless steel alloys was evaluated. The chemical compositions of these alloys are shown in Table 1. The experimental alloys were designed to have compositions similar to that of type AISI 310 stainless steel, a highly alloyed austenitic material that is normally produced without any deliberate nitrogen addition. This steel was selected as the base alloy for this investigation because it solidifies as austenite and remains fully austenitic down to room temperature. This prevents any bulk solid-state phase transformations, which may lead to changes in the solid-state nitrogen solubility in the alloy, from taking place after solidification.

In order to study the influence of the original base metal nitrogen content on nitrogen absorption and desorption during welding, the experimental alloys were produced with three nitrogen concentrations:

- a *low* nitrogen level (residual nitrogen content of approximately 0.005%),
- a *medium* nitrogen level (approximately 0.1%), and
- a *high* nitrogen level (approximately 0.25%). This nitrogen level corresponds to the equilibrium nitrogen solubility limit in these steels calculated at a temperature of 1600°C and a nitrogen pressure of 1 atm (Ref. 23).

The influence of the surface-active element concentration on nitrogen absorption and desorption during welding was evaluated by producing each of the low, medium, and high nitrogen experimental alloys described above with two different sulphur concentrations:

- a *low* sulphur content (approximately 0.02%), and

- a *high* sulphur content (approximately 0.05%).

The low-sulphur level shown above falls well within the specified sulphur concentration range for Type AISI 310 stainless steel. As an alternative to varying the sulphur content of the base metal, small amounts of oxygen can be added to the shielding gas during welding, thereby varying the absorbed oxygen content of the weld metal. Varying the sulphur content of the base metal was preferred during this investigation because it provides more accurate control of the surface-active element concentration of the weld metal.

Welding Procedure

All the stainless steel samples were hot-rolled to a thickness of 6 mm, thoroughly ground to remove any scale or surface oxides, and degreased using acetone. The samples were then welded in an enclosed glove box using an automatic autogenous gas tungsten arc welding process. Direct current electrode negative polarity and a 2% thoriated tungsten electrode were used. In order to prevent contamination from the atmosphere due to air entrapment in the arc, the glove box was flushed with pure argon for at least 15 min prior to welding, and a low flow rate of argon was maintained through the box during welding to ensure a slight positive pressure inside the glove box. Shielding was supplied by shielding gas flowing through the welding torch at a pressure of 1 atm and a flow rate of 20 L/min. Welding was performed using a current of 150 A, an arc length of 2 mm, and a welding speed of 2.7 mm/s. Pure argon and four premixed shielding gases, listed below, were used to evaluate the influence of nitrogen additions to argon shielding gas on the absorption and desorption of nitrogen:

- pure argon,
- argon–1.09% N₂,
- argon–5.3% N₂,
- argon–9.8% N₂, and
- argon–24.5% N₂.

All the stainless steel alloys listed in Table 1 were welded using these shielding gases and welding parameters. After weld-

Table 2 — Average Weld Metal Nitrogen Contents of the Different Welded Samples (Percentage by Mass)

| Alloy | Comments | Base Metal N Content | Weld Metal N Content for Various Shielding Gas Compositions | | | | |
|---------|------------------|----------------------|---|-------------------------|------------------------|------------------------|-------------------------|
| | | | Pure Ar | Ar-1.09% N ₂ | Ar-5.3% N ₂ | Ar-9.8% N ₂ | Ar-24.5% N ₂ |
| VFA 657 | Low N, Low S | 0.005% | 0.017% | 0.082% | 0.196% | 0.242% | 0.257% |
| VFA 658 | Medium N, Low S | 0.105% | 0.105% | 0.166% | 0.230% | 0.245% | 0.270% |
| VFA 659 | High N, Low S | 0.240% | 0.216% | 0.240% | 0.267% | 0.265% | 0.277% |
| VFA 752 | Low N, High S | 0.006% | 0.016% | 0.082% | 0.180% | 0.184% | 0.194% |
| VFA 753 | Medium N, High S | 0.097% | 0.118% | 0.150% | 0.220% | 0.230% | 0.226% |
| VFA 755 | High N, High S | 0.280% | 0.271% | 0.280% | 0.331% | 0.325% | 0.330% |

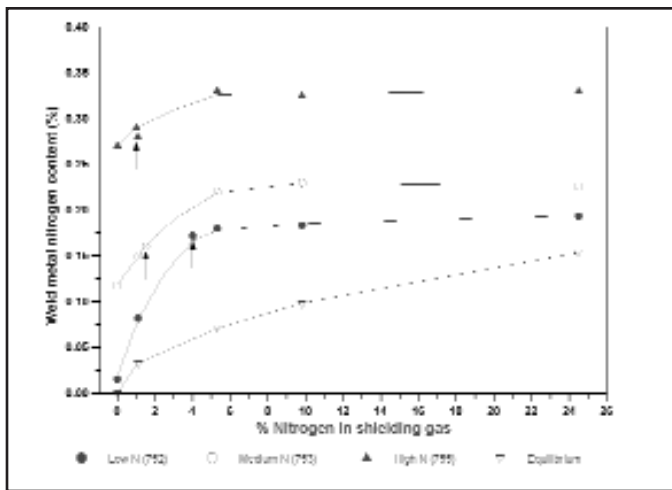


Fig. 3 — Weld metal nitrogen concentration as a function of the shielding gas nitrogen content for the experimental high-sulphur alloys. The arrows indicate the minimum shielding gas compositions where bubbling was observed experimentally.

ing, the nitrogen content of each weld was analyzed using an inert gas fusion analysis technique, taking care to remove the metal drillings required for analysis only from the weld. At least two analyses were performed on each sample to ensure adequate repeatability.

Bubble Formation in the Weld Pool during Welding

As stated earlier, the weld metal nitrogen content usually increases rapidly with an increase in the shielding gas nitrogen content at low-nitrogen partial pressures, followed by steady-state behavior where nitrogen absorption from the arc is balanced by nitrogen evolution from the weld pool. This steady-state region is associated with violent degassing and nitrogen bubble formation. In order to prevent severe nitrogen losses from nitrogen-alloyed stainless steels and to prevent the formation of nitrogen-induced porosity in welds, shielding gas nitrogen contents associated with steady-state behavior must be avoided. The shielding gas nitrogen content at the onset of bubble formation was determined for each of the alloys listed in Table 1 by using a range of argon-nitrogen

shielding gases, mixed using a system of flowmeters. The flowmeters were calibrated to supply shielding gas with the desired argon-nitrogen ratio at a total flow rate of 20 L/min to the welding torch. The shielding gas nitrogen content was increased from 0.5% to 5% in 0.5% increments, and the arc, weld pool, and completed weld were examined visually during and after welding to determine the minimum shielding gas nitrogen level

associated with the onset of significant bubble formation. This point was characterized by severe degassing, spattering, and violent metal expulsion from the molten weld metal. The nitrogen contents of the welds corresponding to the onset of steady-state behavior in each alloy were determined using inert gas fusion analysis techniques.

Measuring the Weld Pool Temperature during Welding

In order to compare the actual nitrogen content of each weld with the calculated equilibrium nitrogen solubility limit, the weld pool temperature had to be determined. An indication of the temperature of the molten weld metal during welding was obtained by measuring the temperature of the center of the weld pool, based on the assumption that rapid convection in the weld pool ensures a fairly homogeneous temperature distribution in the molten metal during welding. The temperature measurement was performed by inserting a thermocouple into the weld pool behind the arc during welding. The thermocouple was shielded from exposure to the arc by a ceramic sheath

that left only the fused end of the wires uncovered. Accurate placement of the thermocouple in the center of the pool was facilitated by an adjustable steel guide tube attached to the main body of the welding torch, and the thermoelectric signal from the thermocouple was recorded using a calibrated XY recorder.

Initial experiments using this arrangement and the welding parameters described earlier were unsuccessful since the weld pool proved to be too shallow to allow full insertion of the thermocouple without fusing the wires to the bottom of the pool. Kuwana et al. (Ref. 30) performed similar experiments and concluded that the weld pool temperature during autogenous arc welding is not influenced to any significant extent by the welding current but is determined principally by the liquidus temperature of the alloy. Based on the conclusions of these authors, the welding current was raised in an attempt to increase the size and depth of the weld pool while maintaining the arc length and travel speed at the values described above. In order to confirm the conclusions of Kuwana et al., the weld pool temperature was measured and compared at two different welding currents, 300 and 350 A. Two measurements were performed at each current setting. The four measurements yielded an average weld pool temperature of 1722°C ± 14°. The results proved to be very repeatable and no significant differences were detected between the temperatures measured at the different welding currents. The conclusion can therefore be drawn that the weld pool temperature during autogenous gas tungsten arc welding is not a strong function of the welding current, and that the temperatures measured at high current values will be equally valid at a current of 150 A.

Results and Discussion

The Influence of the Shielding Gas Nitrogen Content on the Weld Nitrogen Level

The average weld metal nitrogen contents measured in the different samples are

Table 3 — Minimum Shielding Gas Nitrogen Content Required to Initiate Steady-State Behavior and Bubble Formation (Percentage by Mass)

| Alloy | Comments | Minimum Shielding Gas N Content Required to Initiate Degassing | Corresponding Weld Metal N Content |
|---------|------------------|--|------------------------------------|
| VFA 657 | Low N, Low S | 4.5% | 0.160% |
| VFA 658 | Medium N, Low S | 2.5% | 0.200% |
| VFA 659 | High N, Low S | 1.5% | 0.250% |
| VFA 752 | Low N, High S | 4.0% | 0.172% |
| VFA 753 | Medium N, High S | 1.5% | 0.160% |
| VFA 755 | High N, High S | 1.0% | 0.290% |

given in Table 2 and represented graphically in Figs. 2 and 3 for the low- and high-sulphur alloys, respectively. The equilibrium nitrogen solubility, also shown in Figs. 2 and 3, was calculated at the measured weld pool temperature of $1722^{\circ}\text{C} \pm 14^{\circ}$ for each nitrogen partial pressure using Wada and Pehlke's equations and interaction parameters (Ref. 23).

The influence of nitrogen additions to argon shielding gas on the weld nitrogen content of autogenous welds appears to be consistent with that described in literature for carbon and stainless steels. The weld nitrogen content initially increases as the shielding gas nitrogen content increases and then reaches a constant steady-state concentration that is independent of the actual nitrogen partial pressure. The weld nitrogen contents exceed the equilibrium solubility at all partial pressures investigated. This is consistent with available literature (Refs. 12, 13, 15, 16) and confirms that Sievert's law is not obeyed during arc welding. The high-nitrogen solubility limit in the presence of an arc plasma is generally attributed to the presence of monatomic nitrogen in the arc (Refs. 16–18).

The influence of the base metal nitrogen content on the absorption and desorption of nitrogen during welding appears to be dependent on the surface-active element concentration in the weld. In the low-sulphur alloys (Fig. 2), an increase in the initial base metal nitrogen level causes an increase in the weld nitrogen content at low-nitrogen partial pressures. At higher nitrogen partial pressures, the nitrogen content of the welds approaches a steady-state value that is very similar for all three low-sulphur alloys and virtually independent of the base metal nitrogen content. In the case of the high-sulphur alloys (Fig. 3), an increase in the base metal nitrogen content results in higher weld nitrogen contents over the entire range of nitrogen partial pressures evaluated, including a significant increase in the steady-state nitrogen concentration. This is contrary to the conclusions of Okagawa et al. (Ref. 6) and Suutala (Ref. 25) that the nitrogen content of welds is not influenced by the base metal nitrogen

content. This inconsistency can be attributed to the low base metal nitrogen and sulphur levels in the alloys studied by these authors.

The results shown in Figs. 2 and 3 indicate that a high weld metal sulphur content reduces the steady-state nitrogen concentration in the case of the low-nitrogen alloys. This suggests that, in the absence of significant amounts of nitrogen in the base metal prior to welding, the surface-active element concentration mainly influences the rate of nitrogen absorption from the arc atmosphere. The sulphur content also has a significant influence on the weld metal nitrogen content in alloys containing high levels of base metal nitrogen, with higher sulphur concentrations leading to considerably higher levels of nitrogen after welding. High base metal nitrogen contents also appear to increase the level of supersaturation in the weld metal over that required for the nucleation of nitrogen bubbles at atmospheric pressure. Since a higher weld sulphur concentration implies increased weld pool surface coverage, the higher nitrogen levels in the presence of higher surface-active element concentrations suggest that the nitrogen desorption reaction is retarded, consistent with the findings of Battle and Pehlke (Ref. 31) and Katz and King (Ref. 16). More of the nitrogen initially present is therefore maintained in solution and the original nitrogen content is expected to have a more significant influence on the subsequent weld nitrogen concentration — Fig. 3. This is consistent with the results of Arata et al. (Ref. 26), who showed that the total weld metal nitrogen content is the sum of the residual nitrogen content of the base metal and any nitrogen picked up from the interaction between the shielding gas and the molten weld metal. The influence of sulphur on the nitrogen desorption rate is expected to be stronger than on the absorption rate since nitrogen evolution requires two surface sites for the recombination of nitrogen atoms to form N_2 , whereas the absorption of monatomic nitrogen from the arc requires only one surface site per atom dissolved. The valid-

ity of these conclusions will be considered in Part 2 of this study when the nitrogen absorption and desorption reaction rate constants in the experimental alloys will be determined as a function of the surface-active element concentration.

The Minimum Shielding Gas Nitrogen Content that Leads to Bubble Formation in the Weld Pool

In order to determine the minimum shielding gas nitrogen content necessary to induce steady-state behavior and, consequently, nitrogen bubble formation in each of the alloys investigated, the shielding gas nitrogen content was increased from 0.5% to 5% in 0.5% increments during welding. Based on visual observations of the arc and weld pool during welding and the appearance of the completed weld, the minimum shielding gas nitrogen contents that lead to nitrogen bubble formation, and the corresponding weld nitrogen contents, are shown in Table 3 for the experimental alloys.

It is evident that the minimum shielding gas nitrogen content required to initiate bubble formation depends on the base metal nitrogen content and the surface-active element concentration. The saturation limit is reached at progressively lower shielding gas nitrogen contents as the base metal nitrogen level increases. This confirms that base metal nitrogen participates in the nitrogen absorption and desorption reactions during welding. Less nitrogen is required in the shielding gas to reach the saturation limit and initiate steady-state behavior in the high-sulphur alloys because an appreciable fraction of the nitrogen already present in the base metal is prevented from escaping by the higher level of surface coverage. A significant amount of the nitrogen present in the base metal prior to welding is therefore available to participate in the nitrogen absorption/desorption reactions in addition to any nitrogen absorbed from the shielding gas during welding.

Conclusions

- Nitrogen absorption and desorption reactions in the presence of nitrogen-containing shielding gas during the autogenous welding of stainless steel do not obey Sievert's law. The weld metal nitrogen content initially increases with an increase in the shielding gas nitrogen content at low nitrogen partial pressures. At higher partial pressures a dynamic equilibrium is created where the amount of nitrogen absorbed by the weld metal is balanced by the amount of nitrogen evolved from the weld pool during welding.
- The nitrogen content of autogenous stainless steel welds is a function of the ni-

trogen partial pressure in the shielding gas, the base metal nitrogen content, and the surface-active element concentration in the weld metal. In alloys with low surface-active element concentrations, the steady-state nitrogen content of the weld metal is not influenced to any significant extent by the base metal nitrogen content. In the case of alloys with high surface-active element concentrations, an increase in the base metal nitrogen content results in higher weld metal nitrogen contents over the entire range of nitrogen partial pressures evaluated, including a significant increase in the steady-state nitrogen concentration. It is postulated that the surface-active element concentration in the weld metal influences the nitrogen absorption and desorption rates by occupying surface sites required for the absorption of monatomic nitrogen from the arc plasma and the recombination of nitrogen atoms to form N_2 (desorption).

- The minimum shielding gas nitrogen content required to induce steady-state behavior and nitrogen bubble formation in the experimental alloys is also a function of the base metal nitrogen content of the alloy and the surface-active element concentration. The weld metal saturation limit is reached at progressively lower shielding gas nitrogen contents as the base metal nitrogen level increases. It is postulated that less nitrogen is required in the shielding gas to reach the saturation limit in the high-sulphur alloys because an appreciable fraction of the nitrogen already present in the base metal is prevented from escaping by the higher level of surface coverage.

Practical Implications

Nitrogen losses from nitrogen-alloyed stainless steels can be expected during autogenous welding in pure argon shielding gas. Small amounts of nitrogen can be added to the shielding gas to counteract this effect, but this should be done with care to prevent bubble formation. Supersaturation before bubble formation does, however, extend the range of shielding gas compositions that can be used.

Higher concentrations of surface-active elements maintain more of the base metal nitrogen originally present in the alloy in solution in the weld pool. Higher sulphur contents also increase the steady-state nitrogen content and the amount of nitrogen that can be accommodated prior to nitrogen bubble formation. Although higher sulphur contents may not be viable in practice, small amounts of oxygen added to the shielding gas during welding will have a similar effect.

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