Introduction

Cromanite™ is a new high-strength austenitic stainless steel recently introduced into the South African market by Columbus Stainless. It is a high manganese, high nitrogen stainless steel with a chemical composition as shown in Table I.

Nitrogen is a very effective austenite-forming element, that is, it enlarges the austenite phase field on a phase diagram at the expense of ferrite. By stabilizing the austenitic microstructure down to room temperature, the nitrogen alloying additions in Cromanite can replace most of the nickel usually added to austenitic stainless steels. This translates into a substantial reduction in alloying element costs. Nitrogen also increases the strength of stainless steels, without a significant loss in toughness, and has a beneficial effect on certain corrosion properties.

In order for the beneficial effects of high nitrogen contents in stainless steel to be realized, the nitrogen has to be retained in solid solution in the austenite. Precipitation of nitrides or carbonitrides can result in a decrease in ductility, lower resistance to stress-corrosion cracking and changes in the phase balance. The nitrogen added to Cromanite is retained in solid solution by ensuring a high nitrogen solubility limit in the steel. Chromium and manganese are particularly effective in increasing the solubility of nitrogen in stainless steel.

Historically, high manganese, high nitrogen stainless steels have been produced in pressurized furnaces, where a high nitrogen partial pressure is maintained above the melt to force the nitrogen into solution in the steel. In the case of Cromanite, the high manganese and chromium levels increase the nitrogen solubility in the steel to such an extent that it can be produced under atmospheric pressure using conventional steel making processes. This significantly reduces production costs. The production route currently used to produce Cromanite at Columbus Stainless is:

1. Electric arc furnace (EAF)
2. Decarburizing vessel
3. Continuous slab caster

Table I

<table>
<thead>
<tr>
<th>Cr</th>
<th>Mn</th>
<th>N</th>
<th>Ni</th>
<th>C</th>
<th>Balance</th>
</tr>
</thead>
<tbody>
<tr>
<td>19.0</td>
<td>10.0</td>
<td>0.5</td>
<td>0.9</td>
<td>0.03</td>
<td>Balance</td>
</tr>
</tbody>
</table>

Synopsis

Cromanite™ is a new high-strength austenitic stainless steel developed by Columbus Stainless. It contains approximately 19 per cent chromium, 10 per cent manganese and 0.5 per cent nitrogen. Cromanite can be welded successfully, but due to the high nitrogen content of the base metal, certain precautions have to be taken to ensure sound welds with the desired combination of properties.

Although no matching filler metals are currently available, Cromanite can be welded using a range of commercially available stainless steel welding consumables. Welds produced using E309L, E307, E307Si and E312 filler wires are resistant to hot cracking and the formation of nitrogen-induced porosity, but the hardness, strength, ductility and toughness of the welds are generally inferior to those of the base metal.

In applications where full use is made of Cromanite’s high strength, welds with matching strength levels would be required. In wear applications, where Cromanite is used primarily for its work-hardening properties and corrosion resistance, lower strength welds would probably be acceptable. Welds produced using E307 filler metal demonstrate the best combination of properties for use in wear applications. The welds display high rates of work-hardening that would result in increases in hardness and strength when subjected to abrasive or high impact environments.
The microstructure and mechanical properties of Cromanite™ welds

As a result of its high nitrogen content, Cromanite also displays an excellent combination of mechanical properties (see Table II), including high strength, ductility and excellent toughness.

Cromanite has a high capacity to work-harden under deformation, as evidenced by the appreciable increase in strength during cold rolling shown in Table II. The high rate of work-hardening is mainly as a result of a low stacking fault energy due to the high manganese and nitrogen contents. Cromanite’s work-hardening properties under impact loading are similar to those of Hadfield manganese steel.

Cromanite’s high strength and toughness, combined with good corrosion resistance, render the steel an excellent candidate for materials handling applications involving wet sliding abrasion and high impact abrasion. It is expected to have a major advantage over conventional wear plate materials in materials handling applications where moisture plays a role. This is mainly due to its excellent combination of wear resistance and corrosion resistance. It also has potential for a variety of high strength applications.

Cromanite is currently finding successful application in a wide range of areas, such as:
- Liner plates protecting chutes and conveyors in gold mines
- Launderers in coal wash plants
- Shredders, cane knives and hammers in sugar mills
- Railcar bumper plates
- Bottom plates for electromagnets.

As several of the applications envisaged for Cromanite require welding during the fabrication process, it is important that the weldability of Cromanite be evaluated, suitable filler metals selected and potential problems identified. Due to the high nitrogen content, welding requires special care to ensure that the nitrogen remains in the metal during welding, and that the excellent mechanical properties are maintained.

In order to be classified as a sound weld when Cromanite is welded to itself or to any other material, the welded joint has to satisfy three important requirements:

Resistance to hot cracking during welding

Hot cracking is believed to occur when phases with low melting points form at the grain boundaries of the solid during solidification. These phases are usually enriched in elements such as sulphur and phosphorus, which tend to segregate to the grain boundary regions. The low-melting phases can persist as liquid films at the grain boundaries of the solid at much lower temperatures than the solidus of the bulk material. When the material is subjected to shrinkage-induced strains during cooling, the low strength and ductility of the liquid grain boundary films can result in the formation of cracks.

Fully austenitic stainless steel welds can be very susceptible to hot cracking. In order to guarantee adequate resistance to hot cracking during welding of austenitic stainless steels, it is generally recognized that two conditions have to be met:
- The weld metal has to retain at least 5 per cent δ-ferrite in the microstructure down to room temperature.
- The weld metal has to solidify as primary δ-ferrite, rather than austenite. The δ-ferrite then transforms to austenite at lower temperatures after solidification.

The compositions of austenitic stainless steel welding consumables are usually adjusted to meet these requirements, but when Cromanite is welded, an increase in weld metal nitrogen content due to dilution may result in a shift to primary austenitic solidification and fully austenitic weld metal. For this reason, it is important to evaluate Cromanite welds produced using different filler metals to ensure adequate resistance to hot cracking.

Mechanical properties of the weld metal

The second important requirement that has to be met when Cromanite is welded, is adequate weld metal mechanical properties.

Cromanite is a relatively high-strength material. While lower strength welds are viable in wear environments, applications where Cromanite is used primarily for its high strength, such as structural fabrications, would require conformance to stricter acceptance standards. These standards are usually specified by applicable codes, such as BS EN 288. The codes generally specify that the transverse tensile strength of the welded specimen should not be less than the corresponding specified minimum value for the parent metal.

Nitrogen solubility in the weld metal

The third important requirement concerns the solubility of nitrogen in the weld metal. It is likely that the nitrogen content of the weld metal will increase during welding as a result of dilution with the high nitrogen parent plate. At the elevated temperatures encountered during the weld thermal cycle, nitrogen diffusion into the weld metal from the parent plate (adjacent to the fusion line) could also play a role. If the nitrogen level in the weld exceeds the solubility limit at any time prior to solidification, nitrogen bubbles can form in the liquid, thus increasing the likelihood for nitrogen porosity. In order to reduce the possibility of nitrogen-induced porosity, the solubility of nitrogen in the weld metal has to be high enough to accommodate the increased nitrogen level. As chromium and manganese are known to increase the solubility limit of nitrogen in austenitic stainless steel, high levels of these elements are desired in the weld metal when filler metals for welding Cromanite are selected.

<table>
<thead>
<tr>
<th>Table II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Published mechanical properties of Cromanite⁴</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Thermo-mechanical history</th>
<th>Yield strength (R_p0,2)</th>
<th>Tensile strength (R_m)</th>
<th>Elongation</th>
<th>Toughness (CVN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>As hot rolled</td>
<td>750 MPa</td>
<td>950 MPa</td>
<td>40%</td>
<td>150 J</td>
</tr>
<tr>
<td>As hot rolled and annealed</td>
<td>550 MPa</td>
<td>850 MPa</td>
<td>50%</td>
<td>250 J</td>
</tr>
<tr>
<td>As hot rolled, annealed and cold worked (50%)</td>
<td>1700 MPa</td>
<td>1720 MPa</td>
<td>10%</td>
<td>-</td>
</tr>
</tbody>
</table>

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There are currently no matching filler metals commercially available for joining Cromanite. The aim of this investigation was to identify commercially available stainless steel welding consumables suitable for joining Cromanite, and to evaluate the resulting welds against the three requirements listed previously.

**Experimental procedure**

During the course of the project, four commercially available stainless steel filler metals were selected and evaluated against the requirements discussed earlier. Typical compositions of the four consumables are shown in Table III.

All the consumables selected for this investigation are generally recommended for welding austenitic manganese steels. E309L is a low carbon, high alloy Cr-Ni stainless steel filler metal, often recommended to minimize the effects of excessive dilution on weld metal properties. E307 stainless steel has lower chromium and nickel levels, but high manganese and carbon contents. E307Si is a locally manufactured consumable that is similar to E307, with slightly higher silicon and manganese contents, and lower nickel and chromium levels. Weld deposits produced using E307 and E307Si are work-hardenable. E312 is commonly recommended for welding steels with low weldability. Its high chromium content generally results in high weld metal δ-ferrite contents. E312 weld deposits are resistant to hot cracking and tolerant to dilution.

During the course of the investigation, a series of Cromanite to Cromanite welds were produced by joining 12 mm thick annealed Cromanite plates using the filler metals shown in Table III. The gas metal arc welding (GMAW) process and single-V weld preparations were used. Shielding gas containing 98 per cent argon and 2 per cent oxygen was used for E309L, E307 and E307Si, and a 75 per cent argon-25 per cent carbon dioxide shielding gas mixture was used for E312 (as recommended by the electrode manufacturers.) Welding was performed semi-automatically, and three passes were required to complete each weld.

The welded samples were sectioned and the weld metal microstructures, mechanical properties and nitrogen levels were investigated. A diagram indicating the location of the different test specimens are shown in Figure 1.

**Microstructure**

The microstructure of each weld was investigated in order to determine whether the requirements for hot cracking resistance were met. The microstructures were sectioned, and samples mounted and polished. The polished samples were etched using Beraha’s etchant for stainless steel and photomicrographs of the resulting weld microstructures were taken. The ferrite number (FN), which defines the ferrite content of the weld by its magnetic response, was measured for each weld using a calibrated Fischer Ferritscope™.

**Mechanical properties**

In order to characterise the mechanical properties of the welded joints, the strength and ductility of each weld were measured using transverse tensile tests (the weld was located perpendicular to the direction of applied stress during the tensile test). Tensile specimens with gauge length-to-diameter ratios of 5 to 1 were used. The toughness of the weld metal was measured by performing room temperature Charpy impact tests according to ASTM A370–771. In addition, hardness profiles were measured across the welded joints using a calibrated Vickers micro-hardness tester. The mechanical properties of the welds were compared to the properties of annealed Cromanite also measured during the course of the project.

**Nitrogen solubility**

In order to determine whether nitrogen was picked up by the weld metal during welding due to dilution with the Cromanite parent metal, the nitrogen content of each weld was measured using inert gas fusion analysis. In addition, the equilibrium nitrogen solubility in each of the filler metals was calculated in order to compare the actual nitrogen levels in the weld with the amount of nitrogen that can dissolve in the metal. Wada and Pehlke’s equations and interaction parameter values were used. After welding, the weld metal...
The microstructure and mechanical properties of Cromanite™ welds

of each sample was inspected visually and microscopically for
any evidence of nitrogen-induced porosity.

Results and discussion

Microstructure and resistance to hot cracking

The room temperature microstructure and solidification mode
of austenitic stainless steel welds are determined principally
by the chemical composition, and in particular by the balance
between austenite- and ferrite-forming elements. Weld
parameters only have a secondary influence on the
microstructure. By depicting the relationship between
austenite- and ferrite-forming elements in the form of Ni-
and Cr-equivalents, diagrams such as the WRC-1992 consti-
tution diagram can be used to predict the microstructure
and solidification mode of stainless steel welds. Such a
diagram, with the positions of Cromanite, E309L, E307,
E307Si and E312 indicated, is shown in Figure 2. The
influence of dilution on the weld microstructure and solidifi-
cation mode can be predicted using tie lines connecting the
different filler metal positions with the position of the base
metal (Cromanite). Increasing levels of dilution will shift the
weld metal composition towards the position of the base
metal along the tie line. The diagram predicts that Cromanite
welds produced using E309L, E307, E307Si and E312
solidify with δ-ferrite as leading phase (the Ferrite and FA
fields on the diagram), regardless of the amount of dilution
with the Cromanite base metal, whilst retaining varying
amounts of δ-ferrite in the microstructure down to room
temperature.

Typical weld metal microstructures of Cromanite welds
joined using E309L, E307, E307Si and E312 are shown in
Figures 3, 4, 5 and 6 respectively. The measured ferrite
number (FN) of each weld is shown in brackets in the Figure
caption. The ferrite numbers correspond well with the
predicted ferrite contents, as shown in the WRC-1992
diagram in Figure 2.

The Fe-Cr-Ni ternary system provides the basis for
discussing phase equilibrium in austenitic stainless steels. By
selecting a vertical section at 70 per cent iron, shown in
Figure 7, the possible phase transformations during solidifi-
cation can be approximated. Depending on the chemical composition, and in particular the balance between austenite- and ferrite-formers (as represented by the Cr- and Ni-equivalents, rather than the actual chromium and nickel contents), an austenitic stainless steel can solidify by primary separation of austenite (at the nickel-rich side of the diagram to the right of the eutectic L+γ+δ triangle) or δ-ferrite (at the chromium-rich side of the diagram to the left of the eutectic triangle) from the melt. The initial solidification product is dependent only on the composition of the melt at the liquidus temperature.

The weld metal microstructures of welds produced using E309L, E307 and E307Si filler wires (Figures 3, 4 and 5) are similar and consist of an austenite matrix (light coloured phase) with small amounts of vermicular (feathery) δ-ferrite (dark coloured phase). The vermicular morphology and presence of δ-ferrite at the original dendrite cores in these structures confirm the prediction of the WRC-1992 diagram that the weld metal solidifies as δ-ferrite. The weld metal compositions are probably situated on the chromium-rich side of the Fe-Cr-Ni phase diagram in Figure 7, most likely near the eutectic triangle. The first δ-ferrite to form at the original dendrite cores in these welds is highly enriched in ferrite-forming elements, such as chromium, and depleted in austenite-formers, and therefore remains stable down to room temperature as the vermicular δ-ferrite network. The remainder of the δ-ferrite transforms to austenite on cooling.

The higher Cr-equivalent to Ni-equivalent ratio of E312 results in a high level of retained δ-ferrite (FN 38,2) in the weld metal microstructure (Figure 6), although dilution with the high nitrogen parent metal causes a significant decrease in δ-ferrite content, compared to the undiluted filler metal composition (along the tie line in Figure 2). The high δ-ferrite content causes a change in δ-ferrite morphology from a vermicular morphology to a more blocky structure. The high levels of retained δ-ferrite in the room temperature microstructure and the blocky morphology of the δ-ferrite provide further evidence that the weld solidifies as primary δ-ferrite. The weld metal composition is probably situated more towards the chromium-rich side of the phase diagram in Figure 7, further to the left of the eutectic triangle. At lower temperatures the δ-ferrite partially transforms to austenite.

The presence of significant amounts of δ-ferrite in the structure of the respective welds at elevated temperatures during solidification (as predicted by the WRC-1992 diagram), and retained in the weld microstructure down to room temperature, suggests that all the welds investigated fulfill the requirements for hot cracking resistance. The conclusion can be drawn that the welds will not be susceptible to hot cracking during welding. This was corroborated by the absence of cracks in the weld metal microstructures.

**Mechanical properties of the weld metal**

The average mechanical properties of Cromanite to Cromanite welds joined using E309L, E307, E307Si and E312 filler wire are shown in Tables IV and V. The results of the transverse tensile tests indicate that the strength and ductility of the welded samples are generally appreciably lower than those of annealed Cromanite. As a result, fracture occurred in the weld metal of all the samples tested. The welds joined using E307 appear to have the best combination of properties, demonstrating a large degree of work-hardening and uniform elongation prior to fracturing. The high rate of work-hardening can be attributed to a low stacking fault energy as a result of the high manganese and low nickel contents of the microstructure and mechanical properties of Cromanite™ welds

![Figure 7—Vertical section at 70 per cent Fe (percentage by mass) of the Fe-Cr-Ni ternary system](image-url)

**Table IV**

<table>
<thead>
<tr>
<th>Material</th>
<th>Yield strength $R_{P0.2}$ [MPa]</th>
<th>Tensile stress $R_m$ [MPa]</th>
<th>Hardness (Vickers)</th>
</tr>
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<tbody>
<tr>
<td>Cromanite (annealed)</td>
<td>587</td>
<td>916</td>
<td>277</td>
</tr>
<tr>
<td>Welded sample (E309L)</td>
<td>475</td>
<td>620</td>
<td>183</td>
</tr>
<tr>
<td>Welded sample (E307)</td>
<td>556</td>
<td>823</td>
<td>187</td>
</tr>
<tr>
<td>Welded sample (E307Si)</td>
<td>450</td>
<td>681</td>
<td>186</td>
</tr>
<tr>
<td>Welded sample (E312)</td>
<td>629</td>
<td>791</td>
<td>235</td>
</tr>
</tbody>
</table>
The microstructure and mechanical properties of Cromanite™ welds

Table V

<table>
<thead>
<tr>
<th>Material</th>
<th>% Elongation at failure (A)</th>
<th>% Reduction in area at failure (Z)</th>
<th>Toughness CVN [J]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cromanite (annealed)</td>
<td>75</td>
<td>60</td>
<td>298</td>
</tr>
<tr>
<td>Welded sample (E309L)</td>
<td>24</td>
<td>53</td>
<td>105</td>
</tr>
<tr>
<td>Welded sample (E307)</td>
<td>45</td>
<td>46</td>
<td>104</td>
</tr>
<tr>
<td>Welded sample (E307Si)</td>
<td>43</td>
<td>29</td>
<td>132</td>
</tr>
<tr>
<td>Welded sample (E312)</td>
<td>28</td>
<td>36</td>
<td>52</td>
</tr>
</tbody>
</table>

E307 filler wire. The high rate of work-hardening results in high weld metal strength and ductility values. (The percentage elongation shown in Table V for annealed Cromanite is higher than the published value shown in Table II. This can be explained by a difference in specimen dimensions, as the percentage elongation measured during a tensile test depends on the gauge length of the samples.)

The weld produced using E312 filler wire has high strength and hardnes values, probably due to the presence of significant amounts of δ-ferrite in the microstructure. The δ-ferrite will provide some second phase strengthening.

Although the welds have relatively high impact toughness values, the toughness of all the welds is significantly lower than that of annealed Cromanite at room temperature. In particular, the high δ-ferrite content of E312 weld metal results in an impact toughness well below that of Cromanite. The decrease in toughness as a result of high levels of δ-ferrite suggests that duplex ferrite-austenite filler metals, such as E312, should not be used in applications requiring high impact strength.

Hardness profiles across the welds are shown in Figure 8. The curves indicate that the average weld metal hardness of welds produced using E309L, E307 or E307Si filler wire is significantly lower than the hardness of the annealed Cromanite base metal (as indicated by the dashed line in Figure 8). In-service work-hardening under conditions of impact or high stress abrasion will probably cause a substantial hardness increase in the case of welds produced using E307, reducing the hardness difference between the weld metal and the parent plate. For this reason, E307 is recommended as a filler metal for joining Cromanite for wear applications. The hardness of the weld metal produced using E312 is higher, compared to E309L, E307 and E307Si, but still well below the hardness of the base metal.

Nitrogen solubility in the weld metal

The weld metal nitrogen content of each weld, measured by an inert gas fusion analysis technique, is shown in Table VI. Since no deliberate nitrogen additions are generally made to the weld metal (E312), the equilibrium nitrogen solubility limit of the four filler metals was calculated according to Wada and Pehlke’s equations and interaction parameter values. The calculated solubilities are shown in Table VI. It has to be emphasised that Wada and Pehlke’s equations cannot be used to provide exact values for the nitrogen solubility in the weld metal, as thermal equilibrium is generally not obtained in the weld pool. For this reason the results shown in Table VI only provide approximate values for the amount of nitrogen that can be absorbed by the weld pool prior to nitrogen bubble formation. Although nitrogen is absorbed by the weld pool during welding, the results indicate that the actual weld metal nitrogen content of each weld is still well below the corresponding calculated solubility limit.

Visual and microscopic inspection of the welds did not reveal the presence of appreciable levels of nitrogen-induced porosity in any of the welds. The results suggest that nitrogen-induced porosity need not be considered a problem when Cromanite is joined using E309L, E307, E307Si or E312 filler wire. This is probably due to the low residual nitrogen levels in the weld pool prior to welding. Even though the nitrogen content of the weld metal tends to increase during welding due to dilution, high nitrogen levels can be tolerated in the weld metal before the solubility limit is exceeded (as shown in Table VI). As a result, nitrogen evolution from the weld metal and the formation of porosity were marginal for the welds investigated.

Table VI

<table>
<thead>
<tr>
<th>Material</th>
<th>Measured nitrogen content</th>
<th>Nitrogen solubility limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weld metal (E309L)</td>
<td>0,145%</td>
<td>0,304%</td>
</tr>
<tr>
<td>Weld metal (E307)</td>
<td>0,111%</td>
<td>0,267%</td>
</tr>
<tr>
<td>Weld metal (E307Si)</td>
<td>0,155%</td>
<td>0,259%</td>
</tr>
<tr>
<td>Weld metal (E312)</td>
<td>0,167%</td>
<td>0,420%</td>
</tr>
</tbody>
</table>
Even though porosity does not appear to be a problem when joining Cromanite using the filler metals shown in Table III, low heat inputs and interpass temperatures (below approximately 175°C) are recommended during welding, where possible, to keep the weld pool small and to minimize any potential nitrogen losses.

Summary and conclusions

Cromanite is a new high-strength austenitic stainless steel produced by Columbus Stainless. Its combination of wear resistance and corrosion resistance renders it an excellent candidate for materials handling applications involving wet sliding abrasion and high impact abrasion. It has already been used successfully in a number of prototype applications.

Although no matching filler metals are currently available, Cromanite can be welded using a range of commercially available stainless steel welding consumables. Welds produced using E309L, E307, E307Si and E312 filler wires are resistant to hot cracking and the formation of nitrogen-induced porosity. The hardness, strength, ductility and toughness of the welds are generally inferior to those of the base metal. As a result, tensile specimens tend to fracture in the weld metal.

Even though more work would be required before Cromanite can be used in critical applications where welds would have to conform to strict acceptance standards, welds with lower strength and toughness properties would probably be viable in wear applications. In wear environments, where Cromanite is used primarily for its work-hardening properties and corrosion resistance, the marginally lower strength of the weld metal will not have a detrimental influence. Welds produced using E307 filler wire demonstrate the best combination of properties for use in wear environments. The low nickel content of E307 results in a high rate of work-hardening that would probably result in an increase in hardness and strength when the weld is subjected to high impact or abrasion conditions. For this reason, E307 is recommended for welding Cromanite for wear applications.

Acknowledgements

Special thanks to Columbus Stainless for sponsoring the project and performing the nitrogen analyses, and the University of Pretoria for providing laboratory facilities. The assistance of Johann Borman and Marius Els is also gratefully acknowledged.

References
