1.4669, a new lean duplex stainless steel with improved toughness and machinability

N. Renaudot, E. Chauveau, M. Mantel

Among duplex stainless steels, the lean duplex family is a quite new family, still in expansion. It allows a good corrosion resistance, most of the time over that of a standard 4301 austenitic grade, to high mechanical properties, far higher than that of a 4301, and to a low amount of expensive alloying elements such as nickel compared to that of a 4301.

But when these grades are produced in high diameter bars, they often present a bad toughness and a poor machinability, these properties being critical when trying to use such high diameter bars in various applications. For example, the well-known 4062 and 4162 grades present an impact strength below 100 J at 20°C and below 50 J at -46°C on ∅73mm bars. Moreover, their machinability in terms of tool wear and chip breakability is below that of 4301 grades, especially when these last ones are of an improved machinability version, such as UGIMA®. The poor machinability of these lean duplex grades is mainly due to their high mechanical properties which induce high cutting forces on the tools during a machining operation, thus, rapid tool wear, and is also due to their very low sulphur content (less than 10ppm) which does not help the chip breaking contrarily to what happens on a 4301 grade with 0,025%S.

It is the reason why UGITECH developed these last few years the 1.4669, a new lean duplex grade with a lower nitrogen content and a higher copper content in order to improve the toughness of this kind of grades and to lower the tool wear rates when machining them via a decrease of the cutting forces on the tools. Moreover, a control of the inclusions in the grade was performed in order to improve the chip breakability of the grade when machined. Of course, this new grade keeps a corrosion resistance over that of a standard 4301.

INTRODUCTION

Among duplex stainless steel, the lean duplex family is a quite new family, still in expansion. The most known are the 1.4062 and the 1.4162 Lean Duplex Stainless Steels (LDSS). Compared to the 1.4362, these new LDSS have a lower amount of expensive alloying elements such as nickel (between 1,5 and 3% compared to the 4,5% of the 1.4362). To keep a good ratio between ferrite and austenite (not so far from 50/50) in these two LDSS, their N was raised from around 0,12% to 0,2% and, in 1.4162, chromium was slightly decreased (from 22-23% for 1.4362 to 21% for 1.4162). The consequences of these chemical analysis modification are multiple as detailed in paragraphs 1 to 3: loss in toughness, in machinability (in terms of tool wear rates), and in some cases in corrosion resistance compared to the standard 1.4362. So the question is: how can we improve the machinability and toughness of a LDSS, without too expensive alloying elements and keep, at the same time, a corrosion resistance equal of over that of a 1.4301 austenitic SS?

TOUGHNESS OF 1.4062 AND 1.4162 LDSS

Different ∅73mm bars of 1.4062, 1.4162 and 1.4362 were industrially produced in order to compare their toughness, corrosion resistance and machinability. The chemical analysis of these bars are given in the table 1.

All of the duplex bars have a low O level (around 30-40ppm) and a very low S level (less than 10ppm) in order to avoid any effect of these elements on the properties of the bars. The industrial heat treatment done on the duplex bars after their hot rolling is a quenching from 1050°C (LDSS) or 1030°C (1.4362) to limit the precipitations (Cr2N, ...) which can induce loss of toughness or corrosion resistance. Despite these precautions, the toughness of LDSS bars (A1 to A3 and B1) are far below that of 1.4362 bars (C1 and C2) (see table 2).

For each heat, a Ferrite Number (FN) was calculated (see formula and values in table 2) which estimate their ferrite content after quenching. Regarding the evolution of the toughness of these bars with their FN, it seems that, the higher the FN, the lower the toughness (see figure 1). This result can easily be explained by an easier crack propagation in ferrite when the amount of ferrite in the bars is higher. So, to improve the toughness of the LDSS bars, decreasing their FN seems to be a good solution.

This idea was tested, for example, with the #A3 bars with a FN of 53.4 compared to 59.6 and 63.9 of A1 and A2. This FN decrease have led to a far better toughness (241 J at room temperature against 51 and 64 J for A1 and A2; 53 J at -46°C against 12 and 19 J for A1 and A2).

CORROSION RESISTANCE OF 1.4062 AND 1.4162 LDSS

Pitting potentials in a NaCl solution (5%, 35°C) were measured on 1.4062 and 1.4162 specimens from heats #A1, A2, A3 and
### Chemical Analysis

<table>
<thead>
<tr>
<th>Grade</th>
<th>Heat #</th>
<th>C (%)</th>
<th>Si (%)</th>
<th>Mn (%)</th>
<th>Ni (%)</th>
<th>Cr (%)</th>
<th>Mo (%)</th>
<th>Cu (%)</th>
<th>N (%)</th>
<th>S (ppm)</th>
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<tr>
<td></td>
<td></td>
<td>A1</td>
<td>0.027</td>
<td>0.59</td>
<td>1.18</td>
<td>2.66</td>
<td>23.30</td>
<td>0.25</td>
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</tr>
<tr>
<td>1.4062</td>
<td>A2</td>
<td>0.018</td>
<td>0.51</td>
<td>1.24</td>
<td>2.76</td>
<td>23.33</td>
<td>0.26</td>
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<td></td>
<td>A3</td>
<td>0.014</td>
<td>0.40</td>
<td>1.19</td>
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<td>22.44</td>
<td>0.08</td>
<td>0.18</td>
<td>0.192</td>
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<td>B1</td>
<td>0.025</td>
<td>0.48</td>
<td>4.92</td>
<td>1.62</td>
<td>21.46</td>
<td>0.32</td>
<td>0.38</td>
<td>0.208</td>
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<td>C1</td>
<td>0.026</td>
<td>0.49</td>
<td>1.14</td>
<td>4.26</td>
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<td>22.23</td>
<td>0.27</td>
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<td>1.4301</td>
<td>D1</td>
<td>0.050</td>
<td>0.37</td>
<td>0.64</td>
<td>8.53</td>
<td>18.21</td>
<td>0.39</td>
<td>0.54</td>
<td>0.060</td>
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### Mechanical Properties and Impact Strength

<table>
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<tr>
<th>Grade</th>
<th>Heat #</th>
<th>UTS_{20°C} (MPa)</th>
<th>YS_{20°C} (MPa)</th>
<th>A_{20°C} (%)</th>
<th>KV_{20°C} (J)</th>
<th>KV_{46°C} (J)</th>
<th>FN (%)</th>
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<tr>
<td></td>
<td></td>
<td>A1</td>
<td>714</td>
<td>554</td>
<td>41</td>
<td>51</td>
<td>12</td>
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<tr>
<td>1.4062</td>
<td>A2</td>
<td>698</td>
<td>561</td>
<td>41</td>
<td>64</td>
<td>19</td>
<td>63.9</td>
</tr>
<tr>
<td></td>
<td>A3</td>
<td>689</td>
<td>517</td>
<td>46</td>
<td>241</td>
<td>53</td>
<td>53.4</td>
</tr>
<tr>
<td>1.4162</td>
<td>B1</td>
<td>712</td>
<td>540</td>
<td>44</td>
<td>94</td>
<td>42</td>
<td>56.1</td>
</tr>
<tr>
<td></td>
<td>C1</td>
<td>663</td>
<td>427</td>
<td>46</td>
<td>355</td>
<td>124</td>
<td>48.5</td>
</tr>
<tr>
<td>1.4362</td>
<td>C2</td>
<td>656</td>
<td>482</td>
<td>47</td>
<td>382</td>
<td>220</td>
<td>48.7</td>
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<td>1.4301</td>
<td>D1</td>
<td>610</td>
<td>363</td>
<td>57</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
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</table>

(a): FN = 6 (%Cr + 1.32%Mo + 1.27%Si) – 10 (%Ni + 24%C + 16.15%N + 0.5%Cu) – 21.17

### Machinability of 1.4062 and 1.4162 LDSS

∅ 73mm bars from heats #A1, B1 and C2 were tested in two different turning tests in order to measure their machinability. The first test, the VB_{15/0.15}, allows to measure, for a given tool, and for standard feed rate (0.25mm/rev) and depth of cut (1.5mm), the cutting speed for which the flank wear of the tool is 0.15mm in 15 min of effective cutting. The higher the speed, the better the grade; i.e. for a grade with a higher VB_{15/0.15} than another one, the wear rate of the tool, for a given cutting speed, is lower with this grade than with the other one.

The second one, the Chip Breaking Zone (CBZ), allows to measure, for a given cutting speed, the domain, in terms of feed rate “f” and depth of cut “a_p”, for which the chip are well-broken, i.e. not too long. Widening this CBZ is important to lower the risks of chip tangling around the tool and premature tool breaking; so the
wider the CBZ, the better the grade. To measure the CBZ, 56 cutting conditions from \( f = 0.1 \text{ mm/rev} \) to 0.4 \( \text{mm/rev} \) (every 0.05\( \text{mm/rev} \) \( \rightarrow \) 7 conditions) and from \( a_p = 0.5 \text{ mm} \) to 4 \( \text{mm} \) (every 0.5\( \text{mm} \) \( \rightarrow \) 8 conditions) are tested, and the chip are compared to standard chip shapes of the ISO3685 norm. The size of the CBZ is thus defined by the number of cutting conditions (over the 56 tested) for which the chip have a good shape. Of course, the higher the number of good conditions, the better the grade. All these CBZ are done at the same cutting speed in order to be able to make a good comparison between the different grades, even if these CBZ does not change a lot when the cutting speed is modified.

**VB\(_{15/0.15}\) results**

A slight but significant decrease of the VB\(_{15/0.15}\) in turning for LDSS (220 m/min) is observed when compared to that of 1.4362 (235 m/min), itself slightly lower than that of a standard 1.4301 (240 m/min) (see table 4).

To understand these differences, cutting forces on the tools (\( F_x, F_y, F_z \)) were measured thanks to a Kistler sensor in the same cutting conditions for the 4 grades. Tests were done at \( V_c = 200 \text{ mm/min} \), \( f = 0.25 \text{ mm/rev} \) and \( a_p = 1.5 \text{ mm} \) on industrial \( \odot 73 \text{mm} \) bars from \( \odot 62 \text{ and } \odot 59 \text{ mm} \); the total cutting forces \( F \) (\( = [F_x^2 + F_y^2 + F_z^2]^{1/2} \)) were measured during 1 min of continuous cutting and then translated in specific cutting force \( K_c \) (\( = F / (f . a_p) \)). Table 4 shows the average specific cutting forces measured for the 4 different grades. As expected, the higher the \( K_c \), the lower the VB\(_{15/0.15}\); the 2 LDSS with the highest \( K_c \) (over 2600 MPa) present the lowest VB\(_{15/0.15}\) (220 m/min) whereas the 1.4362 and 1.4301, with a significantly lower \( K_c \) (around 2450 MPa) present higher VB\(_{15/0.15}\) (around 235 \( \rightarrow \) 240 m/min).

The \( K_c \) differences observed between the 2 LDSS and the 1.4362 could be explained either by differences in their dislocation behavior or differences in their austenite stability against strain-induced martensite formation. So, to have an idea of the austenite stability in LDSS and 1.4362 against strain-induced martensite formation, estimation of the chemical analysis of their austenite were made using standard partitioning coefficient between ferrite and austenite for the different elements (see table 5) and the Md30 of these austenite phases were calculated. Of course, the lower the Md30, the more stable the austenite. Since the calculated Md30 of 1.4362 is far over that of 1.4062 and at the same level than that of 1.4162, the lower \( K_c \) of 1.4362 cannot be explained by a more stable austenite. Moreover, it was already seen [1] that, even in the less stable austenite (that of 1.4362), no strain induced martensite can be formed in the conditions of machining (too high temperatures and strain rates). It was verified by magnetic measurement. As it can be seen in table 6, there is no significant increase of the percentage of magnetic phases between the non deformed material (60mm tubes obtained from 73mm bars of heat #C1) and the corresponding chips (obtained by an orthogonal turning operation on the same 60mm tubes).

<table>
<thead>
<tr>
<th>Grade</th>
<th>Heat #</th>
<th>SECO TM2000 CNMG 120408-MF4</th>
<th>STELLRAM SP0819 CNMG 120408E4E</th>
<th>Average values for the 2 different cutting tools ( (1) )</th>
<th>( K_c ) ( (2) )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>VB(_{15/0.15}) CBZ</td>
<td>VB(_{15/0.15}) CBZ</td>
<td>VB(_{15/0.15}) CBZ</td>
<td>( K_c ) (MPa)</td>
</tr>
<tr>
<td>1.4062</td>
<td>A1</td>
<td>230 26</td>
<td>210 26</td>
<td>220 26</td>
<td>2 672</td>
</tr>
<tr>
<td>1.4162</td>
<td>B1</td>
<td>220 24</td>
<td>220 24</td>
<td>220 24</td>
<td>2 625</td>
</tr>
<tr>
<td>1.4362</td>
<td>C2</td>
<td>235 11</td>
<td>235 13</td>
<td>235 12</td>
<td>2 450</td>
</tr>
<tr>
<td>1.4301</td>
<td>D1</td>
<td>250 33</td>
<td>230 37</td>
<td>240 35</td>
<td>2 442</td>
</tr>
</tbody>
</table>

\( (1) \) SECO TM2000 CNMG 120408-MF4 and STELLRAM SP0819 CNMG 120408E-4E;

\( (2) \) Average values measured during 1 min at \( V_c = 200 \text{ m/min} \), \( f = 0.25 \text{ mm/rev} \), \( a_p = 1.5 \text{ mm} \) (from \( 62 \text{ to } 59 \text{ mm} \)).

**TAB. 4 VB\(_{15/0.15}\) and CBZ in turning of different \( \odot 73 \text{mm} \) bars of 1.4062, 1.4162, 1.4362 and 1.4301.**

VB\(_{15/0.15}\) e CBZ (Chip Breaking Zone) nella tornitura di barre \( \odot 73 \text{mm} \) di diversi acciai 1.4062, 1.4162, 1.4362 e 1.4301.
So the higher $K_c$ obtained for LDSS can only be explained by their dislocation behavior during the cutting tests. This behavior is probably linked to the lower Ni as well as the higher N in LDSS: first, the lower Ni induces a lower Stacking fault Energy (SFE) for LDSS (see for instance [2]) thus reducing the screw dislocation annihilation mechanism; It leads to higher strain hardening and higher $K_c$. second, the higher N (which is mainly in austenite) is known to induce lower SFE for austenite (see [3, 4] for instance) but also to block strongly (more than C) the dislocations [5] leading to a higher strain hardening and higher $K_c$.

Because an improvement of the VB15/0.15 of LDSS could be very useful to help the substitution of 1.4301 by a LDSS for bar markets, a decrease of the strain hardening (for example by a not too high N content and/or a decrease of the Cr content) could be interesting.

CBZ results

The important widening of the CBZ of LDSS compared to the 1.4362 CBZ (see table 4) seems to be in correlation with the lower elongation of LDSS, their higher FN, lower toughness and higher N content. So it is difficult to know what is the preponderant parameter which act on the chip breakability.

A previous study on 1.4462 grades [1] seems to show that FN (and toughness) are preponderant and that N level (which is mainly in austenite) is not. Tables 7 and 8 sum up these previous results on 1.4462 Ø 60mm bars. They show that the higher their FN, the lower their toughness and the wider their CBZ, even if the N content of heat #E3 is the lowest.

So, thanks to their higher FN (and lower toughness), LDSS heats #A1 and B2 have wider CBZs than the 1.4362 heat #C2. But compared to the CBZ of a 1.4301, especially in a UGIMA® version (which is the case of #D1), the CBZ of these LDSS remains narrower than that of 1.4301 (see table 4). Thus a widening of the CBZ of LDSS by increasing the strain hardening element levels (like N) could be useful.

HOW TO IMPROVE MACHINABILITY AND TOUGHNESS OF A LEAN DUPLEX WITHOUT DECREASING ITS CORROSION RESISTANCE?

As it was shown in paragraph 1, to improve the toughness of a LDSS, the decrease of its FN seems to be a good solution. It could be obtain by the increase of the most austenitising elements (C, N, Ni, Cu) and/or decrease of the most ferritising ones (Mo, Si, Cr).
But, in 1.4062 and in 1.4162, it is quite difficult to obtain this good toughness by a low FN, because Ni, N and C cannot be raised:

- Ni must be kept at a low level for cost reasons,
- N was raised at its maximum level (to avoid the formation of blowholes during the continuous casting),
- C cannot be increased without bad effect on the tool wear rates in machining (see in paragraph 5 the #F2 example).

And Si, Mo and Cr cannot be lowered:

- Si and Mo are already at very low levels;
- Cr cannot be lowered below 22% without decreasing the PREN, which governs the pitting corrosion resistance of these LDSS (see paragraph 2).

So the only way to improve the toughness of LDSS without decreasing their pitting corrosion resistance or the machining tool life (their VB15/0.15) seems to be the increase of the Cu content in these grades over the limits of both 1.4062 and 1.4162 norms.

TAB. 9  
Analysis and mechanical characteristics of Ø 73mm bars tested in turning.  
Analisi e proprietà meccaniche di barre Ø 73mm sottoposte a prova in tornitura.

A LEAN DUPLEX WITH COPPER TO IMPROVE TOUGHNESS AND LOWER THE CUTTING TOOL WEARS

In accordance with the discussion in paragraph 4, the newly developed LDSS, the 1.4669, have a high amount of Cu (around 2.5%) to allow a ratio between ferrite and austenite around 50/50 (and thus guaranty and good toughness even on high diameter bars) and also to allow to decrease the N content to around 0.15% in order to improve the rather low VB15/0.15 of the 1.4062 grade.

To confirm these hypothesis, a first heat (#F1) of 1.4669 was industrially produced and transformed in ∅73mm bars. As expected, the impact strength of these bars are far over that of 1.4062 (A1) and 1.4162 (B1) (see table 9).

FIG. 3  
VB15/0.15 and CBZ size with a STELLRAM SP0819 CNMG 120408E-4E tool for different LDSS Ø 73mm bars.  
Entità di VB15/0.15 e di CBZ con utensile STELLRAM SP0819 CNMG 120408E-4E per diverse barre LDSS da Ø 73mm.
and lower level of N have induced the reduction of the specific cutting forces of the 1.4669 heat #F1 (see figure 4).

As expected, #F2 have a lower VB15/0.15 than #F1 because of an increase of its C content which increases the strain hardening coefficient of the grade, so the strengthening of the chips during their formation, thus increasing the specific cutting forces.

Finally, it is confirmed that, in the same time, these differences of chemical analysis induces the opposite effect on the CBZ (see the CBZ in figure 3): as expected, the higher the toughness of the bars, the narrower the CBZ.

A LEAN DUPLEX WITH A INCLUSION CONTROLED PROCESS TO GUARANTY A GOOD CHIP BREAKING IN MACHINING

By increasing the nickel and copper content and decreasing the nitrogen content of the 1.4669 heat #F1 (see figure 4).

As expected, #F2 have a lower VB15/0.15 than #F1 because of an increase of its C content which increases the strain hardening coefficient of the grade, so the strengthening of the chips during their formation, thus increasing the specific cutting forces.

Finally, it is confirmed that, in the same time, these differences of chemical analysis induces the opposite effect on the CBZ (see the CBZ in figure 3): as expected, the higher the toughness of the bars, the narrower the CBZ.

A LEAN DUPLEX WITH A INCLUSION CONTROLED PROCESS TO GUARANTY A GOOD CHIP BREAKING IN MACHINING

By increasing the nickel and copper content and decreasing the nitrogen content of the 1.4669 grade compared to the standard 1.4362 grade, its CBZ was reduced in size. So it was important to try to increase it by producing this grade in a Inclusion Engineered (IE) version, like UGIMA grades. It was done on heat #F3. VB15/0.15 and CBZ for the #F3 heat was compared to that of heats #A1 to F2 in figure 5. As expected, thanks to a quite high level of Ni and Cu (→ high SFE), its rather low level of C and N (→ limited strengthening of the chips during their formation) and the presence of adequate inclusions (IE) in the matrix, the heat #F3 have the highest VB15/0.15 and the widest CBZ.

A LOW SULFUR 22%Cr LEAN DUPLEX TO GUARANTY A GOOD CORROSION RESISTANCE

Finally, localised corrosion resistance tests were done to confirm that the 1.4669 new grade, thanks to a low sulphur level (< 10 ppm) and a Cr level over 22%, have a localised corrosion resistance over that of the 4301 it has to replace on different markets (see figure 6).

CONCLUSIONS

It was shown that the bad toughness of 1.4062 and 1.4162 bars was mainly due to their too high amount of ferrite in them (FN over 55). These high FN are mainly due to an important decrease of their Ni content (for cost reasons) compared to the 1.4362 grade, not totally compensated by a N increase.

In order to lower the FN of LDSS, decreasing their ferritising elements and/or increasing their austenitising ones was investigated:

1. Mo and Si cannot be lowered because they are already in a very small amount; (2) Cr cannot be lowered below 22% in order to keep a pitting corrosion resistance over that of a 1.4301 and it cannot be compensated by N because Cr is the unique element which define the pitting corrosion resistance of the ferrite phase (which is the weak point of the LDSS); (3) Ni cannot be raised
for cost reasons; (4) N and C cannot be raised because of the increase of the cutting tool wear rates they will induce in machining.

Finally, only Cu can be raised to lower the FN and increase the toughness of high diameter bars. Moreover, this Cu increase should decrease the tool wear rates in machining thanks to a decrease of the specific cutting forces on the tools via a lower strain hardening rate during the chip formation. This effect is improved if Cu is raised sufficiently to allow a decrease of the N content without increasing the FN. The decrease of N is possible because, contrarily to the decrease of Cr, it would not have any effect on the pitting corrosion resistance of the LDSS since the weak point of the LDSS is the ferrite phase with nearly 0% of N in it.

It is the reason why a new LDSS grade, the 1.4669, was developed with a FN around 50% in order to have a good toughness even on high diameter bars; it has more than 2% of Ni and 2% of Cu, a rather low amount of nitrogen (less than 0.18%) to lower the tool wear rates in cutting (increase of the VB15/0.15 in turning) compared to other LDSS; moreover the grade was Inclusion Engineered (IE) in order to guaranty a wide CBZ. Finally the level of chromium over 22% allows to guaranty a localised corrosion resistance over that of a 1.4301.

REFERENCES