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

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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.

Keywords:
lean duplex stainless steel; 1.4669; machinability; toughness; corrosion resistance

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 (Cr_2N, ...) 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 64J 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 an NaCl solution (5%, 35°C) where measured on 1.4062 and 1.4162 specimens from heats #A1, A2, A3 and

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Paper presented at the 7th European Stainless Steel Conference - Como, 21-23 September 2011

Grade	Heat #	C (%)	Si (%)	Mn (%)	Ni (%)	Cr (%)	Mo (%)	Cu (%)	N (%)	S (ppm)
1.4062	A1	0.027	0.59	1.18	2.66	23.30	0.25	0.21	0.194	3
	A2	0.018	0.51	1.24	2.76	23.33	0.26	0.20	0.173	3
	A3	0.014	0.40	1.19	2.85	22.44	0.08	0.18	0.192	2
1.4162	B1	0.025	0.48	4.92	1.62	21.46	0.32	0.38	0.208	5
1.4362	C1	0.026	0.49	1.14	4.26	22.15	0.29	0,31	0.117	3
	C2	0.026	0.41	1.05	4.27	22.23	0.27	0.28	0.114	2
1.4301	D1	0.050	0.37	0.64	8.53	18.21	0.39	0.54	0.060	246

TAB. 1 ***Chemical analysis of different ∅ 73mm bars of 1.4062, 1.4162 and 1.4362.***

Analisi chimica di diverse barre di acciaio 1.4062, 1.4162 e 1.4362 con ∅ 73mm.

Grade	Heat #	$UTS_{20°C}$ (MPa)	$YS_{20°C}$ (Mpa)	$A_{20°C}$ (%)	$KV_{20°C}$ (J)	$KV_{-46°C}$ (J)	FN [(a)] %
1.4062	A1	714	554	41	51	12	59,6
	A2	698	561	41	64	19	63.9
	A3	689	517	46	241	53	53,4
1.4162	B1	712	540	44	94	42	56.1
1.4362	C1	663	427	46	355	124	48,5
	C2	656	482	47	382	220	48,7
1.4301	D1	610	363	57	-	-	-

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

TAB. 2
Mechanical properties and impact strength of different ∅ 73mm bars of 1.4062, 1.4162 and 1.4362.

Caratteristiche meccaniche e resistenza all'impatto di diverse barre di acciaio 1.4062, 1.4162 e 1.4362 con ∅ 73mm.

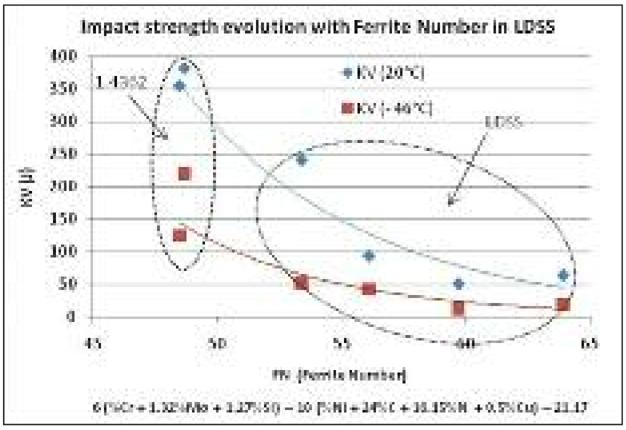

FIG. 1 ***Evolution of the impact strength of different 73mm bars of 1.4062, 1.4162 and 1.4362 with their FN.***

Evoluzione della resistenza all'impatto di barre, con diametro di 73mm, di acciaio 1.4062, 1.4162 e 1.4362 con il relativo FN- Ferrite Number.

B1 and compared to that of a standard 1.4301 (heat #D1). The results obtained are given in table 3. To make a better correlation between the pitting potentials and the PREN of the different LDSS, PREN of ferrite and austenite phases were estimated. For this purpose, γ/α partitioning coefficients for Cr, Mo and N were obtained thanks to microprobe analysis of ferrite and austenite on heat #A1. The γ/α partitioning coefficient were estimated to 0,915 for Cr, 0,66 for Mo and more than 100 for N (no N measurable in ferrite). The estimated $PREN_{\alpha}$ and $PREN_{\gamma}$ are given in table 3. The ferrite appears clearly as the weak point of the LDSS in terms of pitting corrosion resistance (contrarily to what is observed for super duplex grades where Mo allows a good resistance for the ferrite phase).

As expected, the pitting potentials of the LDSS decrease with the decreasing of their $PREN_{\alpha}$ (see table 3 and figure 2). For #A1 and A2, their $PREN_{\alpha}$ of 25.1 (thanks to their high Cr) allows a pitting potential around 400mV/SCE; for #A3 and B1, their lower Cr content (22.44 and 21.46% respectively) leads to a important decrease of their pitting potentials, especially for B1 with a pitting potential below that of 1.4301 (220 mV/SCE).
Of course, the lower the FN in the LDSS, the higher the Cr and Mo in the ferrite, so the higher the $PREN_{\alpha}$. For example, if the FN of #B1 were the same as that of C1, the $PREN_{\alpha}$ of #B1 would be increased from 23.5 to 23.7, and its pitting potential probably slightly increased.
Looking at the partitioning coefficients, it seems that increasing the N content in these LDSS will not have any effect on their pitting corrosion resistance because it will only increase the corrosion resistance of austenite. So the only way to keep a good corrosion resistance for LDSS is to keep their Cr at a quite high level (Mo is too expensive) such as in #A1 and A2.

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 quite important to lower the risks of chip tangles around the tool and premature tool breaking; so the

TAB. 3
Corrosion resistance in NaCl, 5%, 35 °C of different specimens of 1.4062 and 1.4162.

Resistenza alla corrosione in NaCl, 5%, 35 °C, di diversi provini di acciaio 1.4062 e 1.4162.

Grade	Heat #	PREN	$PREN_{\alpha}$	$PREN_{\gamma}$	Epit NaCl 5%, 35 °C (mV/SCE)
1.4062	A1	27.2	25.1	30.4	385
	A2	27.0	25.1	30.3	417
	A3	25.8	23.7	28.2	318
1.4162	B1	25.8	23.5	28.8	162
1.4301	D1	-	-	-	220
PREN = Cr + 3,3Mo + 16N					

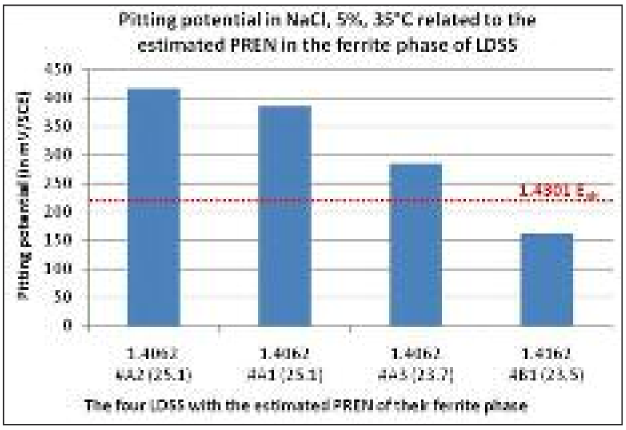

FIG. 2 ***Evolution of the pitting potential in a NaCl solution (5%, 35 °C) for the different 1.4062 and 1.4162 with the estimated PREN of their ferrite phase.***

Evoluzione del potenziale di vaiolatura in una soluzione di NaCl (5%, 35 °C) per i diversi acciai 1.4062 e 1.4162 con il PREN-(Pitting Resistance Equivalent Number) stimato della loro fase ferritica.

wider the CBZ, the better the grade. To measure the CBZ, 56 cutting conditions from f = 0,1 mm/rev to 0,4 mm/rev (every 0,05mm/rev → 7 conditions) and from a_p = 0,5 mm to 4 mm (every 0,5mm → 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 Kisler sensor in the same cutting conditions for the 4 grades. Tests were done at V_c = 200 m/min, f = 0.25 mm/rev and a_p = 1.5 mm on industrial ∅ 73mm bars from ∅ 62 and ∅ 59 mm; the total cutting forces F_c (= $[F_x^2 + F_y^2 + F_z^2]^{1/2}$) were measured during 1 min of continuous cutting and then translated in specific cutting force K_c (= F_c / [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 – 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).

Grade	Heat #	SECO TM2000 CNMG 120408-MF4		STELLRAM SP0819 CNMG 120408E-4E		Average values for the 2 different cutting tools (1)		K_c (2) (MPa)
		$VB_{15/0,15}$	CBZ	$VB_{15/0,15}$	CBZ	$VB_{15/0,15}$	CBZ	
1.4062	A1	230	26	210	26	220	26	2672
1.4162	B1	220	24	220	24	220	24	2625
1.4362	C2	235	11	235	13	235	12	2450
1.4301	D1	250	33	230	37	240	35	2442

(1) SECO TM2000 CNMG 120408-MF4 and STELLRAM SP0819 CNMG 120408E-4E;
(2) Average values measured during 1 min at Vc = 200 m/min, f = 0.25 mm/rev, ap = 1.5 mm (from 62 to 59mm).

TAB. 4 ***$VB_{15/0.15}$ and CBZ in turning of different ∅ 73mm bars of 1.4062, 1.4162, 1.4362 and 1.4301.***

$VB_{15/0.15}$ e CBZ (Chip Breaking Zone) nella tornitura di barre ∅ 73mm di diversi acciai 1.4062, 1.4162, 1.4362 e 1.4301.

grade	#	C (%)	Si (%)	Mn (%)	Ni (%)	Cr (%)	Mo (%)	Cu (%)	N (%)	Md30 [(a)] for γ
1.4062	γ (A1)	0.068	0.50	1.23	3.20	22.05	0.19	0.21	0.487	- 124°C
1.4162	γ (B1)	0.045	0.42	5.08	1.85	20.59	0.26	0.38	0.377	- 41°C
1.4362	γ (C2)	0.052	0.38	1.09	5.41	19.95	0.22	0.32	0.227	- 40°C

(a): Md30 (°C) = 551 – 462(%C + %N) – 9.2%Si – 8.1%Mn – 13.7%Cr – 29(%Ni + %Cu) – 18.5%Mo

TAB. 5 ***Estimation of the chemical analysis of the austenite in #A1, B1 and C2 bars and their Md30.***

Stima dell'analisi chimica dell' austenite in barre #A1, B1 e C2 e rispettivi Md30.

grade	#	% of magnetic phase in non deformed material	% of magnetic phase in chips obtained for f = 0.35mm/rev	% of magnetic phase in chips obtained for f = 0.40mm/rev
4362	C1	44.1	43.0	43.9

TAB. 6 ***Percentage of magnetic phase (ferrite + strain-induced martensite) in non deformed 60mm 4362 tubes and chips obtained by orthogonal cutting of the 60mm 4362 tubes.***

Percentuale di fase magnetica (ferrite + martensite indotta da deformazione) in tubi di acciaio 4362 da 60mm non deformati e trucioli ottenuti mediante taglio ortogonale dei tubi di acciaio 4362 da 60mm.

Grade	#	C (%)	Si (%)	Mn (%)	Ni (%)	Cr (%)	Mo (%)	Cu (%)	N (%)	S (ppm)	FN[(a)]	KV 20°C	KV -46°C
4462	E1	0.018	0.45	0.83	5.51	22.26	3.11	0.20	0.184	12	50.3	337 J	320 J
	E2	0.012	0.51	0.66	5.28	22.53	3.17	0.20	0.166	2	59.6	280 J	41 J
	E3	0.024	0.50	1.45	5.33	22.80	3.44	0.30	0.137	15	64.1	274 J	75 J

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

TAB. 7 ***Chemical analysis of 4462 ∅ 60mm bars, FN and related impact strength.***

Analisi chimica di barre di acciaio 4462 da ∅ 60mm, FN e relativi resistenza all'impatto.

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 $VB_{15/0.15}$ 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.

	#E1	#E2	#E3
FN[(a)]	50.3	59.6	64.1
CBZ*	10	20	18
CBZ**	15	19	22
CBZ (average values)	12.5	19.5	20

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

* Results obtained with SECO TM2000 CNMG 120408 – MF4 tools;

** Results obtained with STELLRAM SP0819 CNMG 120408E – 4E tools.

TAB. 8 ***CBZ results obtained on different 4462 ∅ 60mm bars with 2 different coated carbide turning tools.***

Risultati CBZ ottenuti con diverse barre ∅ 60mm di acciaio 4462 con 2 diversi utensili di tornitura rivestiti di carburi.

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 ∅ 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).

grade	#	C (%)	Si (%)	Mn (%)	Ni (%)	Cr (%)	Cu (%)	N (%)	S (ppm)	Rm (MPa)	$Rp_{0.2}$ (MPa)	KV 20°C (J)	KV - 46°C (J)
1.4062	A1	0.027	0.59	1.18	2.66	23.30	0.21	0.194	3	714	554	51	13
1.4161	B1	0.025	0.48	4.92	1.62	21.46	0.38	0.208	5	712	540	94	42
1.4669	F1	0.025	~ 0.5	1–2	2–3	22–23	1.5–3	0.12–0.18	2	703	515	356	103
	F2	0.045	~ 0.5	1–2	2–3	22–23	1.5–3	0.12–0.18	2	725	590	83	29
1.4669 (IE)	F3	0.025	~ 0.5	1–2	2–3	22–23	1.5–3	0.12–0.18	5	726	508	125	24

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

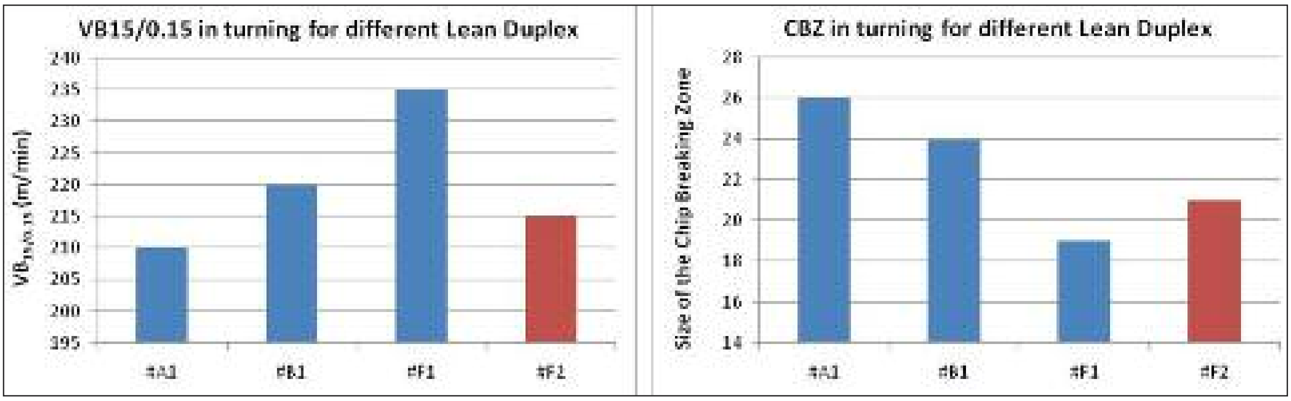

FIG. 3 ***$VB_{15/0.15}$ and CBZ size with a STELLRAM SP0819 CNMG 120408E-4E tool for different LDSS ∅ 73mm bars.***
Entità di $VB_{15/0.15}$ e di CBZ con utensile STELLRAM SP0819 CNMG 120408E-4E per diverse barre LDSS da ∅ 73mm.

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 $PREN_{\alpha}$ 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 $VB_{15/0.15}$) seems to be the increase of the Cu content in these grades over the limits of both 1.4062 and 1.4162 norms. By putting 2% of Cu in, for example, heat #A1, its FN will be lowered to 50.7%, thus inducing probably a very good toughness, even on high diameter bars. But increasing the Cu over 2% in heat #A1 could allow also to lower the N content in it and keep a low FN. So, it is important to know what is the best solution in terms of corrosion resistance and machinability.
Concerning the corrosion resistance, it was shown in paragraph 2 that N have no effect on the pitting corrosion resistance of the LDSS because N is mainly in austenite and its PREN ($PREN_{\gamma}$) is far over that of the ferrite ($PREN_{\alpha}$). So, concerning the pitting corrosion resistance, N can be lowered without bad effect. Of course, Cu effect have to be checked.
Concerning the machinability, two points have to be discussed: the effect of N on the tool wear rates (measured in turning by the $VB_{15/0.15}$ test) and its effect on the chip breakability (measured in turning by the CBZ test). Concerning the tool wear rates, it was shown in paragraph 3 that a decrease of the N content could be good to improve the $VB_{15/0.15}$ thanks to a decrease of the strain hardening of the grade which would induce a decrease of the specific cutting forces on the tools during a cutting operation. Concerning the CBZ, it was shown in paragraph 3 that the most important parameter seems to be the FN (and the toughness). So, improving the toughness by a decrease of the FN (thanks to the Cu increase) will probably reduce the CBZ of the new LDSS. This point must be checked.

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 $VB_{15/0.15}$ 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).
A second heat (#F2) was industrially produced with a higher C content to confirm its bad effect. As expected, the impact strength done on the ∅ 73mm bars from this heat (#F1) were far below that of the first heat (#F1).
Then turning tests were done on the different ∅ 73mm bars from heats #F1 and F2 and compared to that of #A1 and B1. Figure 3 shows the results obtained on these first 4 heats.
As expected, #F1 have a significantly better $VB_{15/0.15}$ than #A1 and #B1 thanks to a higher amount of Cu and to its quite high level of Ni, both acting on reducing the strain hardening of the chips during their formation. Of Course, its lower level of N acts in the same way. As expected, these higher levels of Cu and Ni

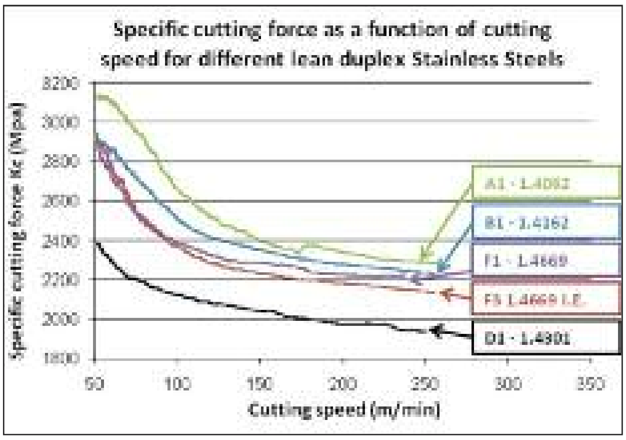

FIG. 4 ***Evolution of the specific cutting force with the cutting speed in a turning operation done on ∅ 73mm hot rolled bars with a SECO TM2000 tool (CNMG 120408-MF4), and with a standard feed rate of 0.25mm/rev and a standard depth of cut of 1.5mm.***

Evoluzione della forza specifica di taglio con velocità di taglio in un' operazione di tornitura eseguita su barre da ∅ 73mm laminate a caldo con utensile SECO TM2000 (CNMG 120408-MF4), e con velocità di avanzamento standard di 0.25mm/rev e profondità di taglio di 1.5mm.

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 $VB_{15/0.15}$ 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 1.4062 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. $VB_{15/0.15}$ and CBZ for the #F3 heat was compared to that of heats

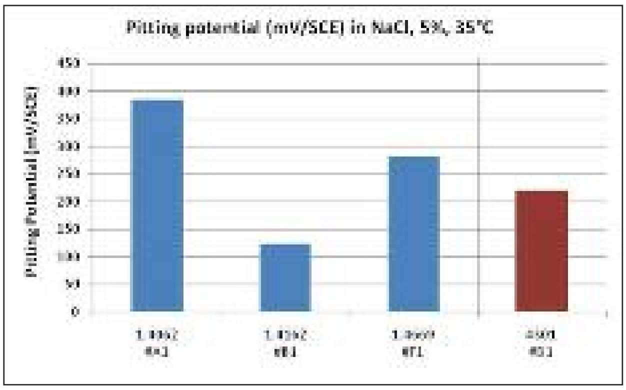

FIG. 6 ***Compared pitting potential of different Lean Duplex with a 4301 reference.***

Confronto del potenziale di vaiolatura tra diversi gradi di Lean Duplex e un acciaio 4301 di riferimento.

#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 $VB_{15/0.15}$ 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 ∅ 73mm 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

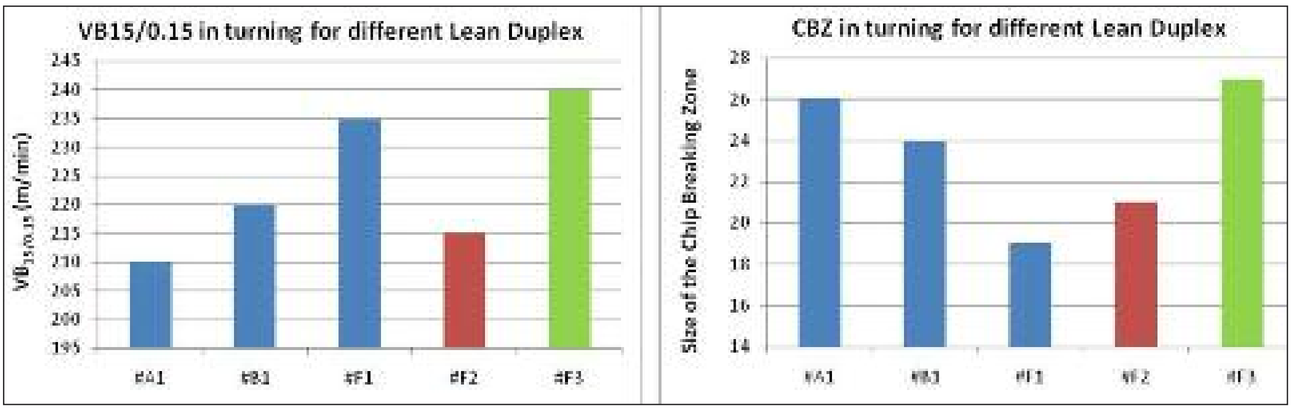

FIG. 5 ***$VB_{15/0.15}$ and CBZ size for different LDSS grades.*** *Entità di $VB_{15/0.15}$ e di CBZ per diversi gradi di acciaio LDSS.*

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 $VB_{15/0.15}$ 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.

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Abstract

1.4669, un nuovo acciaio inossidabile lean duplex con migliorata tenacità

Parole chiave: acciaio inossidabile – proprietà - corrosione

Tra gli acciai inossidabili duplex, la famiglia dei lean duplex rappresenta una novità ancora in espansione. Rispetto ad un acciaio 4301, questa famiglia presenta una buona resistenza alla corrosione, molto spesso oltre il valore standard dell'acciaio austenitico, oltre a elevate caratteristiche meccaniche e ad una bassa quantità di costosi elementi di lega, quali il nichel.
Ma quando questi acciai sono utilizzati nella produzione di barre di diametro elevato, spesso presentano una bassa tenacità e lavorabilità, che caratteristiche critiche quando si tratta di utilizzare tali barre di diametro elevato in diverse applicazioni. Ad esempio, i gradi noti come 4062 e 4162 presentano una resistenza all'urto inferiore ai 100 J a 20 ° C e inferiore ai 50 J a - 46 ° C su barre con diametro di 73mm. Inoltre, la loro lavorabilità in termini di usura dell'utensile e truciolabilità è inferiore a quello degli acciai di grado 4301, specialmente quando questi ultimi sono nella versione a migliorata lavorabilità, come l'acciaio UGIMA®. La scarsa lavorabilità di questi tipi di lean duplex è dovuta principalmente alle loro elevate carartteristiche meccaniche che inducono elevate sollecitazioni degli utensili durante la lavorazione meccanica, e pertanto una loro rapida usura, ed è anche causata dal basso tenore di zolfo (meno di 10 ppm) che non agevola l'asportazione del truciolo contrariamente a quanto avviene per il grado di acciaio 4301 con 0,025% di zolfo.
Per questa ragione UGITECH ha sviluppato in questi ultimi anni l'acciaio 1.4669, un nuovo grado di acciaio bifasico lean con un contenuto di azoto inferiore e un più alto contenuto di rame al fine di migliorare la tenacità di questo tipo di acciai e di abbassare la velocità di usura dell'utensile durante la lavorazione tramite una diminuzione delle forze da applicare sugli utensili. Inoltre, è stato effettuato un controllo delle inclusioni allo scopo di migliorare la truciolabilità di questo acciaio durante la lavorazione. Naturalmente, questo nuovo grado di acciaio mantiene una resistenza alla corrosione superiore a quella di un normale acciaio 4301.