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Stainless Steel, with 11 per cent Chromium and High Yield Strength, for Welded Constructions Resistant to Corrosion and Abrasion

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To increase the life and reduce the maintenance cost of welded structures, the use of stainless steel is appropriate.

Among all the low-cost 11 per cent chromium stainless steels, UGINOX F12N shows the best low-temperature impact strength in the heat-affected zones (HAZ) of welds (80 J/cm^2 at –30 °C, while it is 9 J/cm^2 for a dual-phase stainless steel and less than 1 J/cm^2 for AISI 409 grade). This behaviour is due to the HAZ structure, which comprises at least 90 per cent fine-grained low-carbon martensite. Moreover, the high mechanical strength (0,2 per cent proof stress >340 MPa and elongation >25 per cent) and excellent weldability of UGINOX F12N are equivalent to those of plain carbon and weathering steels. However, in corrosive environments, particularly with concurrent abrasion, UGINOX F12N is vastly superior to ordinary steels.

For applications requiring a combination of high yield strength and toughness in welded joints similar to those of high-strength steels, with a corrosion–abrasion resistance at least equivalent to that of AISI 409 grade, the SUPER F12N grade is suitable. The main mechanical properties are 0,2 per cent proof stress ≥600 MPa, elongation ≥17%, and Charpy V impact at –20 °C ≥70 J/cm^2.

Introduction

For welded construction (railway stock, containers, etc.), carbon steels and weathering steels are widely used. For the construction of frames (side members, cross-pieces, etc.), the use of high-strength low-alloy (HSLA) steels saves the weight of materials. For example, 20 per cent of the materials was saved by the use of HSLA steels for the construction of motor coaches for the French Atlantic TGV high-speed train. But the main problem with carbon, weathering, and HSLA steels is their very low corrosion resistance and their high rate of metal loss. The use of stainless steel containing at least 10,5 per cent chromium increases the life time and reduces the maintenance cost of equipment.

It therefore seems appropriate to try to develop a stainless steel with the following characteristics:

- low cost
- high mechanical properties
- excellent toughness in both welds and base metal
- good resistance to natural atmospheres and contact with moderately aggressive environments
- easy workability when it comes to welding, roll forming, or bending so that it is comparable with carbon steel.

In order to meet all these requirements, UGINE SA commercialized a ferritic stainless steel, UGINOX F12N, and developed another grade, SUPER F12N, with enhanced mechanical properties and better corrosion–abrasion resistance.

TABLE I
TYPICAL CHEMICAL ANALYSIS (MASS %) OF UGINOX F12N AND OTHER MAIN 11 PER CENT CHROMIUM STAINLESS STEELS

Grade	C	Mn	Si	Cr	Ni	Ti	N	γ max*	FF†
AISI 409	0,010	0,400	0,500	11,4	–	>6(C+N)	0,010	0	≥13,5
AISI 420	0,200	0,500	0,400	13,0	0,200	–	0,020	100	–
Dual phase	0,025	1,2	0,400	11,4	0,600	0,300	0,011	70	10
UGINOX F12N	0,060	0,800	0,400	11,0	0,800	0,200	0,020	100	5,6

* γ max = maximum level of austenite[2] around 1050 °C
† FF = Ferrite factor according to Kaltenhauser's formula[3]
FF = % Cr + 6% Si + 8% Ti + 4% Mo – 2% Mn – 4% Ni – 40% (C+N)

UGINOX F12N Stainless Steel

There are several grades of stainless steels having a chromium content of 11 per cent or thereabouts but with different structures[1]:

- ferritic steels (AISI 409 grade)
- martensitic steels (AISI 410 and 420 grades)
- dual-phase steels.

Ferritic steels that are ferritic at all temperatures (the analysis of AISI 409 grade is given in Table I) show ferritic grain growth in the heat-affected zone (HAZ) during welding. The HAZ has a low toughness, which makes this steel unsuitable for use in thick (>1,5 mm) and highly reliable welded assemblies.

Martensitic steels usually contain more than 0,1 per cent carbon (analysis of AISI 420 grade in Table I) and cannot be easily welded owing to the martensite brittleness formed in the welded zone (WZ) and HAZ. This brittleness is due to the extreme hardness of the martensite (600 to 700 Hv for an AISI 420 steel) and the hydrogen uptake in the WZ.

Dual-phase steels (ferrite and austenite at high temperature) that are ferritic or ferritic–martensitic when cooled (analysis in Table I) often show ferritic grain coarsening in the HAZ during welding[4]. The structure of the HAZ leads to a reduction in toughness. For some welded applications, at least 90 per cent martensite is required in the HAZ, which is not possible with these steels.

UGINOX F12N stainless steel was developed for use in structures under stress and, as a result, it is designed to show good weldability and high mechanical properties, particularly with regard to impact toughness.

Chemical Composition of F12N

On the basis of 11 per cent chromium, the sum of carbon and nitrogen content was fixed at less than 0,1 per cent. In order to ensure that it is completely austenitic when heated, gamma-producing elements were added such as nickel (0,8 per cent) and manganese (0,8 per cent). The steel is thus self-hardening and forms a low-carbon, nitrogen martensite[5]. This martensite is not very brittle (360 Hv maximum instead of 600 to 700 Hv for AISI 420 grade), particularly after welding in the WZ and HAZ. Titanium is added in order to form titanium nitrides, instead of chromium nitrides (Cr_2N) since Cr_2N makes the steel brittle[10]. Part of the carbon (0,030 per cent) is in the form of TiC. The ferrite factor, FF, calculated by Kaltenhauser's formula[3], is about 5,6 for F12N, while it is about 13,5 for AISI 409 steel and 10 for dual-phase steel. A typical analysis of F12N is given in Table I.

Metallurgy of F12 N

Continuous cooling transformation diagram (CCT)

Since F12N stainless steel is a weldable steel, the structures present during continuous cooling after austenitizing must be known. The CCT curve determined by dilatometry, hardness, and optical micrography is given in Figure 1. UGINOX F12N (analysis Table I) was austenitized for 30 minutes at 900 °C. On this curve, two different processes can be seen:

- a peak around 600 to 700 °C, which corresponds to conversion of the austenite into ferrite and carbides;
- the 200 to 400 °C temperature interval, which is related to the conversion into martensite of the austenite that has not been transformed into ferrite and carbides.

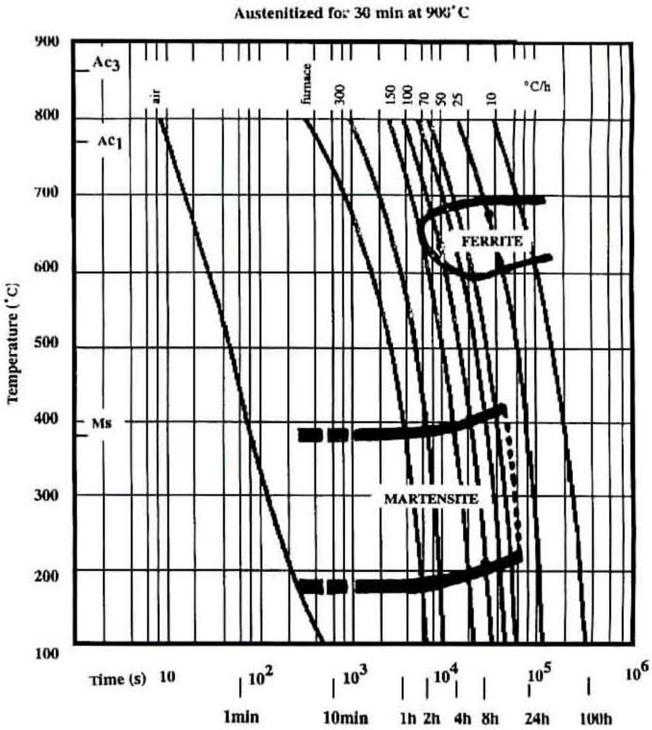

FIGURE 1. Continuous cooling transformation curve of F12N

The analytical balance of F12N and the cooling rate mean that, during welding without filler metals, more than 90 per cent martensite is obtained both in the melted zone and in the HAZ.

The characteristic metallurgical values (Ac_1, Ac_3, and M_s) are summed up in Table II.

TABLE II
CHARACTERISTIC METALLURGICAL VALUES OF UGINOX F12N

Ac_3 (°C)	860
Ac_1 (°C)	770
Ms (°C)	380

Mechanical properties in standard condition at the time of supply

F12N is usually supplied hot-rolled or cold-rolled with ferrite and carbides structure. The mechanical properties of F12N when hot-rolled in a thickness of 5 mm are given in Table III and are compared with those of AISI 409 steel and hot-rolled dual-phase steel.

TABLE III
MECHANICAL PROPERTIES OF UGINOX F12N AND OTHER MAIN 11 PER CENT CHROMIUM STAINLESS STEELS

Grade	Tensile strength MPa	0,2% proof stress MPa	Elongation in 50 mm %
AISI 409	420 – 550	≥250	≥25
Dual phase	≥460	≥280	≥20
UGINOX F12N	450 – 600	≥340	≥25

The impact-toughness transition curves of F12N, AISI 409, and dual-phase steels, both in a 5 mm thick hot-rolled base metal (1/2 KCV), are compared in Figure 2. For each temperature, 3 samples were tested. F12N and dual-phase steels have an impact toughness of 100 J/cm^2 at –20 °C and 150 J/cm^2 at +20 °C. AISI 409 steel, however, has an impact toughness of only 20 J/cm^2 at +20 °C.

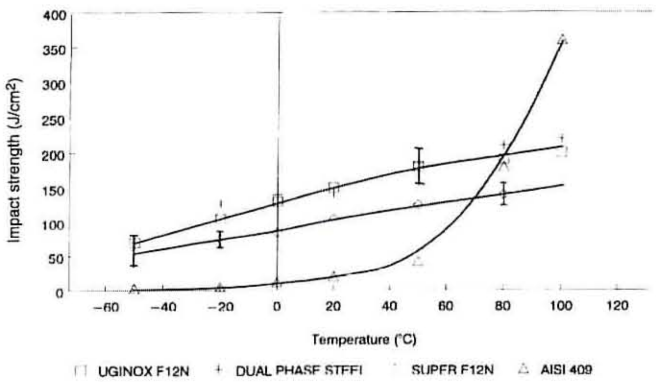

FIGURE 2. Impact toughness transition curves, base metal $^1/_2$ KCV

Characteristics of Welded Joints

Welding without a filler metal was carried out by the TIG (1,5 to 3 mm thick) and PLASMA (for thicknesses of 4 to 6 mm) processes. A protective argon atmosphere was always used on both sides.

Welding with a filler metal was carried out by the MIG process in a 97 per cent argon and 3 per cent oxygen atmosphere.

TIG and PLASMA welding of F12N, AISI 409, and dual-phase steels

Table IV gives the welding parameters for thicknesses of 2 and 6 mm. In the melted zone, the microstructure was martensitic for F12N, mixed (ferrite + martensite) for the dual-phase steel, and completely ferritic for the AISI 409 grade.

TABLE IV
WELDING PARAMETERS USED FOR F12N

Thickness mm	Welding process	Current A	Voltage V	Speed cm/min	Welding energy J/cm
2,0	TIG	220	12	70	2 260
6,0	PLASMA	330	25	25	19 800

For F12N, the HAZ was martensitic, with more than 90 per cent fine grains, while the other two grades were large-grained structures.

MIG welding of F12N, AISI 409, and dual-phase steels

MIG welding was carried out with an ER 309 L filler wire. The 1/2 KCV preparation used on the test specimens with a section of 10 x 5 mm^2 and a half-bevel joint enabled a vertical HAZ to be obtained so that the impact toughness could be measured in the HAZ (notch located in the vertical HAZ, Figure 3), therefore, the HAZ was not symmetrical.

Figure 4 shows that F12N has an excellent impact toughness at low temperatures when compared with the other two grades. For example, at –30 °C, the impact toughness in the HAZ of F12N was 80 J/cm^2, while it was 9 J/cm^2 for the dual-phase steel and less than 1 J/cm^2 for the AISI 409 grade.

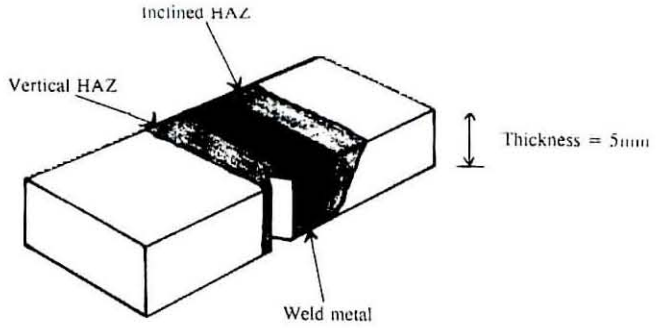

FIGURE 3. Location and orientation of HAZ, Charpy V notched impact specimens

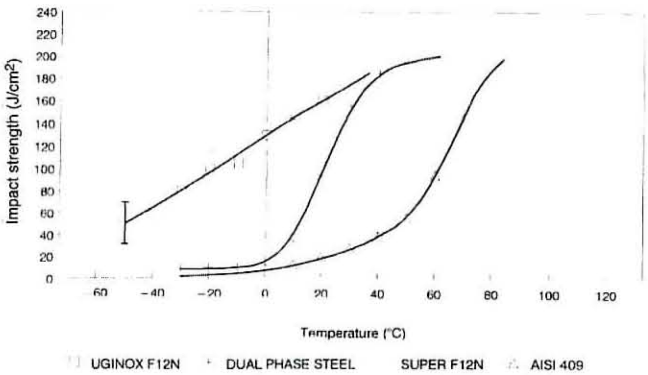

FIGURE 4. Impact toughness transition curves, HAZ $^1/_2$ KCV

Corrosion–Abrasion Resistance of UGINOX F12N

Experimental apparatus

The experimental apparatus that was used is described in detail in the literature[6]. The operating principle is given in Figure 5.

The test specimen was rotated in a corrosive medium containing a fixed quantity of abrasive (99 μm granulometry SiC at a concentration of 25 g/l). This solution was pumped from the bottom of the chamber and sprayed onto the rotating metal surface. The pump rate determined the spraying speed and, therefore, the impact energy of the abrasive particles. The chamber was instrumented so that electrochemical measurements could be taken (monitoring of the rest potential and plotting of polarization curves). The geometry of the chamber remained fixed. Only two parameters could be changed:

- the spraying speed of the fluid onto the metal, which determined the impact energy of the particles, and
- the rotational speed of the specimen (frequency of impact), which determined, among other things, the repassivation ability of the steel grade.

The test specimens were polished with 1200 grade SiC paper before being immersed in the corrosive medium. The specimen was left for 1 hour at rest potential before the test was started.

Deterioration of the metals was expressed by weight loss during the test in mdd (milligrams per square decimetre per

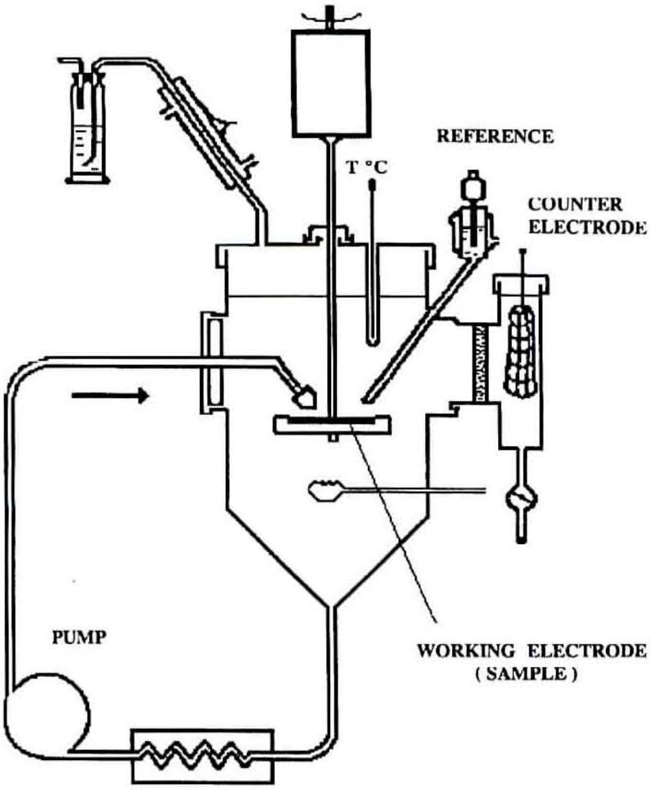

FIGURE 5. Experimental apparatus used in the abrasion–corrosion tests

day). For an iron-based alloy and uniform corrosion, 1 mdd represents a corrosion rate of 5 µm per year.

Tests in a slightly aggressive medium: NaCl at 5.10⁻³M

This solution, containing 170 p.p.m. of Cl^-, corresponds to tap water with a fairly high chlorine content (tap water usually contains 20 to 50 p.p.m. of Cl^-). The duration of the test was 24 hours. In Table V, the behaviour of the F12N steel is compared with a carbon steel and a weathering steel under the two sets of operating conditions. One set (condition 1) is more conducive to corrosion, and the other set (condition 2) to abrasion.

TABLE V
ABRASION-CORROSION RESULTS IN A SLIGHTLY AGGRESSIVE MEDIUM (NaCl AT 5.10^{-3} M) WITH THE TWO SETS OF OPERATING CONDITIONS

Grade	Mass loss mdd	
	Condition 1	Condition 2
UGINOX F12N	12–17	35
Weathering steel	95	128
Carbon steel	113	143

Condition	Rotational speed of specimen r/min	Fluid spraying speed m/s
1	150	3
2	1000	5

The results show that, in both cases, F12N had a greater corrosion resistance than the carbon steel or the weathering steel. In this medium, F12N was sensitive only to abrasion, while the ordinary steels underwent extensive corrosion with a synergistic effect caused by abrasion.

Summary of findings on UGINOX F12N

Among all the low-cost 11 per cent chromium stainless steels, the grade UGINOX F12N showed the best low-temperature impact strength in the HAZ of the welds. This behaviour is due to the HAZ structure, which comprises at least 90 per cent fine-grained low-carbon martensite. Moreover, the high mechanical strength and excellent weldability of UGINOX F12N are equivalent to those of plain carbon and weathering steels. However, in corrosive environments, particularly with concurrent abrasion, UGINOX F12N is vastly superior to ordinary steels.

Super F12N Stainless Steel

SUPER F12N stainless steel is a new steel that offers a yield strength similar to that of high-strength steels, (0,2 per cent proof stress >490 MPa, and elongation >17 per cent), without sacrificing weldability (martensite >90 per cent and high toughness in the HAZ), combined with improved corrosion–abrasion resistance.

Principal Strengthening Mechanisms in Steels

The principal strengthening mechanisms in ferritic stainless steels are martensite formation, work hardening, solid-solution strengthening, and precipitation hardening. In UGINOX F12N, cold working enables the yield strength to be increased only at the expense of a rapid drop in ductility. For example, a thickness reduction of 10 per cent leads to a 0,2 per cent proof strength of 500 MPa but with an elongation of less than 15 per cent. Solid-solution hardening by silicon[7] produces a marked increase in yield strength while conserving a high tensile elongation, but the toughness is reduced significantly (KCV = 10 J/cm^2 at + 20 °C). Precipitation hardening by copper[8] on the one hand and niobium carbonitrides[9] on the other hand proved to be insufficent to attain the target yield strength. The most efficient strengthening process was found to be the martensite transformation.

Martensite Transformation

The chemical composition of UGINOX F12N is given in Table I. During the industrial hot-rolling process, the structure is fully austenitic. After low-temperature coiling, the strip has a 100 per cent martensite structure, with a hardness of about 360 Hv. The industrial cooling rate is sufficiently high (>150 °C/h) to ensure complete transformation of the austenite to martensite without the formation of ferrite and carbides (Figure 1). Because of the low carbon content, the martensite obtained is relatively soft, leading to a tensile strength of 1100 to 1150 MPa, but with an elongation of only 10 per cent. In order to increase the ductility, the martensite must be tempered.

Tempering of the Martensite

Figure 6 shows the hardness obtained after tempering for 8 hours at temperatures between 400 and 800 °C. The softening observed between 400 and 770 °C is due to a decrease in the dislocation density and to the precipitation of carbon from the supersaturated martensite. The carbides formed in the range 300 to 500 °C are known to be of the Cr_7C_3 type[10] while, between 500 and 750 °C, the fine Cr_7C_3 carbides are replaced by $M_{23}C_6$ carbides, which coarsen with increasing time and temperature[10]. Beyond 770 °C (Ac_1 point), the austenite formed produces new martensite on cooling, and

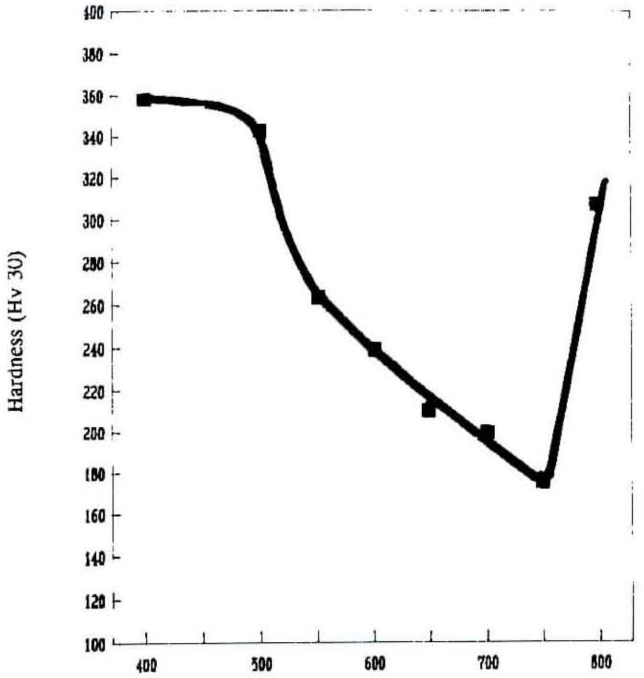

FIGURE 6. Tempering of martensite after 8 h at temperature

the hardness increases again sharply. In industrial practice, tempering is carried out below AC_1. The microstructure obtained is a fine-grained ferrite with a uniform distribution of globular carbides. This is the structure of SUPER F12N.

Mechanical Properties

The mechanical properties obtained on hot-rolled SUPER F12N strip after the industrial tempering treatment are given in Table VI, where they are compared with values for UGINOX F12N and those of a high-strength steel, for thicknesses of 5 and 6 mm. SUPER F12N has properties similar to those of the high-strength steel and considerably better than those of UGINOX F12N. The base-metal impact-strength transition curve is shown in Figure 2. In spite of the high mechanical strength, the toughness also remains high (75 J/cm^2 at –20 °C and 105 J/cm^2 at + 20 °C).

After MIG welding with ER 309 L filler metal (welding conditions identical to those described earlier), the HAZ has a 100 per cent martensite structure. The impact strength at –20 °C is close to 120 J/cm^2 and reaches 150 J/cm^2 at +20 °C.

These excellent property levels are explained by the fine-grained ferrite structure produced by the quenching and tempering treatments.

TABLE VI
MECHANICAL PROPERTIES OF SUPER F12N COMPARED WITH UGINOX F12N AND HSLA STEEL (BASE-METAL THICKNESSES OF 5 AND 6 mm)

Grade	Tensile strength MPa	0,2% proof stress MPa	Elongation in 50 mm %	Charpy V impact at –20°C J/cm^2
SUPER F12N	≥700	≥600	≥17	≥70
HSLA	≥540	≥490	≥18	≥50
UGINOX F12N	450 – 600	≥340	≥25	≥35

Abrasion–Corrosion Tests in a Moderately Aggressive Medium: NaCl at 0,02 M

The experimental apparatus used was described earlier (Figure 5). These tests were carried out as a comparison of the abrasion–corrosion resistance of some 11 per cent chromium stainless steels. The operating conditions were set as follows:

- 1 hour at rest potential
- 24 hours abrasion–corrosion with a rotational speed of 1000 r/min and a spraying speed of 5 m/s
- 1200 SiC grit polishing (the same sample preparation as in the first tests).

Three different steels were tested: UGINOX F12N, SUPER F12N and, as a reference, AISI 409 grade. The mass losses after the tests are given in Table VII.

TABLE VII
ABRASION–CORROSION RESULTS IN A MODERATELY AGGRESSIVE MEDIUM (NaCl AT 0,02 M)

Grade	Mass loss mdd
AISI 409	97 – 105
SUPER F12N	97 – 102
UGINOX F12N	100*–116*–177†

* Slight pitting
† Heavy pitting

Pitting occurred only on the UGINOX F12N, and had a very strong influence on the mass loss during the test. But the SUPER F12N, like the AISI 409 grade, did not experience pitting corrosion. Both these steels have a good abrasion–corrosion resistance. This can also be seen in Figure 7. For UGINOX F12N, the rest potential always decreased, whereas it slowly increased before abrasion and remained stable after abrasion for the AISI 409 grade and SUPER F12N.

This set of operating conditions shows the major influence of corrosion resistance on the tested steels. The hardness seemed to have only a minor effect on the mass loss during the test. So, under these abrasion–corrosion conditions, SUPER F12N has a very good corrosion resistance and can be compared with AISI 409.

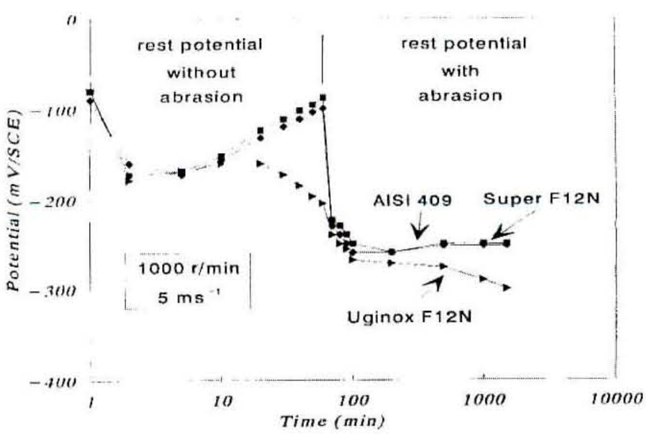

FIGURE 7. Rest potentials for the steels tested

Conclusions

The stainless steel UGINOX F12N has extensive potential applications for high-integrity welded assemblies, where high toughness is required in both welds and base metal. Its weldability and formability are comparable with those of plain carbon or weathering steels. However, in corrosive environments, or in corrosion–abrasion conditions, UGINOX F12N is vastly superior to ordinary steels. It can be used bare but, if painting is necessary, the resulting durability avoids the need for reconditioning. UGINOX F12N is already widely used in transport equipment (railway waggons and containers), in industrial plant (hoppers, conveyors, etc.), and in the building industry.

For applications requiring a combination of high yield strength and toughness in welded joints similar to those of high-strength steels, with a corrosion–abrasion resistance at least equivalent to that of AISI 409 grade, the SUPER F12N grade can be used. This material enables savings in mass to be made in welded structures, while at the same time eliminating the need to provide extra thickness to allow for the metal lost by corrosion.

References

1. Pickering, F. B. (1976). Physical metallurgy of stainless steel developments. *Int. Met. Rev.,* vol. 211. pp. 227–268.
2. Tricot, R., and Castro, R. (1966). Study of the isothermal transformations in 17% Cr stainless steels. *Mémoires Scientifiques Rev. Mét.,* vol. 63, no. 718. pp. 657–684.
3. Kaltenhauser, R. H. (1971). Improving the engineering properties of ferritic stainless steels. *Met. Eng. Quarterly,* vol. 11, May. pp. 41–47.
4. Gooch, T. G., and Ginn, B. J. (1990). Heat-affected zone toughness of SMA welded 12% Cr martensitic–ferritic steels. *Welding Research Supplement,* Nov., pp. 431S–440S.
5. Lefèvre, J., Tricot, R., and Castro, R. (1973). Noveaux aciers inoxydables à 12% de chrome. *Revue de Métallurgie,* Apr. pp. 259–268.
6. Audouard, J. P. (1980). Etude de l'influence des éléments d'alliage sur la passivité d'aciers inoxydables austénitiques à base de chrome et de nickel soumis à l'abrasion des particules solides en suspension dans un milieu corrosif. Ph.D. Thesis, INPG, Grenoble, France.
7. Irvine, K. J., and Pickering, F. B. (1964). High strength 12% chromium steels. In *Metallurgical developments in high alloy steels.* The Iron and Steel Inst. pp. 63–77.
8. Jesseman, R.J., and Murphy, G. J. (1983). Mechanical properties and precipitation hardening response in ASTM A710 grade A and A 736 alloy steel plates. *Conference Proceedings of International Conference on Technology and Applications of HSLA Steels,* 3–6 Oct., Philadelphia. pp. 655–665.
9. Vowles, M. D. J., and West, D. R. F. (1973). Precipitation hardening in iron–chromium–niobium alloys. *J.I.S.I.,* Feb. pp. 147–150.
10. Irvine, K. J., Crowe, D. J., and Pickering, F. B. (1960). The physical metallurgy of 12% chromium steels. *J.I.S.I.,* Aug. pp. 386–405.