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Nitrogen-alloyed austenitic stainless steels and their properties

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SYNOPSIS

This paper reports the results of a literature review carried out on nitrogen-alloyed austenitic stainless steels and their properties. It was found that a large volume of work has been carried out on the subject, particularly with regard to the more common stainless steels such as types 304 and 316. No work appears to have been conducted on the highly alloyed steels such as type 310S.

Nitrogen has been found to increase the stability of the austenite in stainless steels and to impart significant improvements in the mechanical and corrosion properties of these alloys. Importantly, nitrogen appears to increase both the ductility and the strength of austenitic stainless steels over a wide range of temperatures.

SAMEVATTING

Hierdie verslag gee die resultate van 'n literatuuroorsig wat uitgevoer is in verband met stikstofgelegeerde oustenitiese staal en die eienskappe daarvan. Daar is gevind dat daar baie werk in verband met die onderwerp gedoen is, veral wat betref die meer algemene soorte vlekvrye staal soos tipe 304 en 316. Daar is blykbaar geen werk in verband met die hooggelegeerde staalsoorte soos tipe 310S gedoen nie.

Daar is gevind dat stikstof die stabiliteit van die ousteniet in vlekvrye staal verhoog en 'n beduidende verbetering in die meganiese en korrosie-eienskappe van hierdie legerings teweegbring. Wat veral belangrik is, is dat stikstofblykbaar sowel die rekbaarheid as die sterkte van oustenitiese vlekvrye staal oor 'n wye temperatuurstrek verhoog.

INTRODUCTION

The mechanical properties of austenitic stainless steels can be improved by the introduction of an interstitial element in the alloys. Carbon is a very effective element for increasing the strength of common and stainless steels, but its concentration has to be low to avoid sensitization. Although some types of stainless steels possess high strength, these are the exception rather than the rule in that most austenitic stainless steels have very low strength. For example, the yield strength of mild steel is about 300 MPa, which is significantly higher than that of austenitic stainless steel type 304, which is 220 MPa in a similar condition. Thus, significant benefits can accrue from stronger austenitic stainless steels.

Nitrogen can be used as an interstitial alloying element in iron-based alloys. It has been demonstrated that, if nitrogen is substituted for carbon in austenitic stainless steels, the mechanical properties can be improved without any adverse effects on their ductility and corrosion properties.

The main object of this review is to examine the work that has been done on the effects of nitrogen in austenitic steels, particularly those of high chromium and nickel contents. This would form the starting point for research into the effects of nitrogen on the properties of AISI 310S austenitic stainless steel.

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SOLUBILITY OF NITROGEN IN AUSTENITIC STAINLESS STEELS

Vapa and Pehlke[1] studied the solubility of nitrogen in liquid Fe–Cr–Ni, Fe–Cr, and Ni–Cr alloys. They found that the solubility of nitrogen in austenitic stainless steels conforms to Sievert's law, and that chromium markedly increases the solubility of nitrogen in these alloys. It was found in Fe–Cr–Ni alloys that the solubility of nitrogen in the liquid alloy decreased with increasing temperature. Thus, higher concentrations of nitrogen in such alloys would be obtained by an increase in the partial pressure of nitrogen over the alloy and by use of the lowest possible casting temperature.

The effects of alloying elements on the solubility of nitrogen in a liquid Fe–18Cr–8Ni alloy at a pressure of 0,1 MPa and a temperature of 1600°C are summarized in Figure 1. It can be seen that chromium increases the solubility of nitrogen, but nickel, which is the second important element in austenitic stainless steels, decreases it.

Unlike the solubility of nitrogen in liquid Fe–Cr–Ni ternary alloys, that of nitrogen in austenite of high chromium and nickel contents has not been the subject of much research. Recently, the solubility of gaseous nitrogen in austenite was reported by Kikuchi *et al.*[3]. Their results, summarized in Figure 2 for different types of alloys, show that the solubility of nitrogen in Fe–25Cr–20Ni alloy increases with decreasing temperature in the liquid, as well as in the solid. Their results agree with those of Vapa and Pehlke[1].

Austenite can be saturated with nitrogen fairly easily, and the solubility limit of nitrogen in austenite can be varied by variation of the process conditions. Holzgruber[4] recently reviewed the development of processes for the production of high-nitrogen steels (Table I). Each process has different

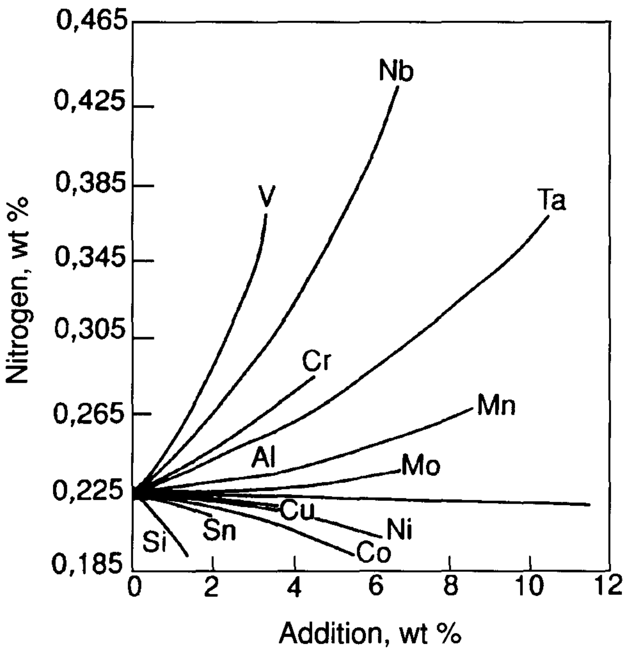

Figure 1—Effect of alloying on the solubility of nitrogen in a liquid Fe–18Cr–8Ni alloy at 0,1 MPa partial pressure of nitrogen and 1600°C

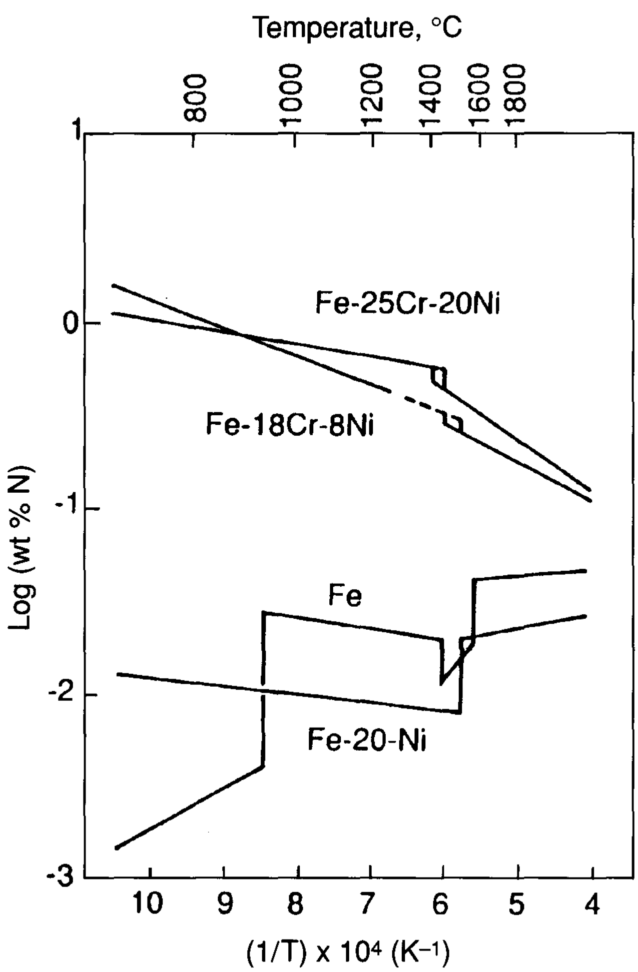

Figure 2—Temperature dependence of nitrogen solubility at 1 atm. pressure of nitrogen in iron and three austenitic stainless steels[3]

constraints that are related to the production capacity, rate of production, and compositional homogeneity of the ingots. However, plasma-arc melting and electroslag remelting are the most efficient processes for introducing high concentrations of nitrogen into steel. The achievement of a nitrogen content of 1 wt per cent is possible by these methods[2].

EFFECT OF NITROGEN ON LATTICE PARAMETERS

Nitrogen as an interstitial element occupies the octahedral voids in fcc crystals, which will accommodate a sphere with a maximum size of 0,414·*R*, where *R* is the atomic radius in nanometres. Table II lists the effects of nitrogen and carbon on the lattice parameters of different alloys.

From Table II, the influence of nitrogen and carbon on fcc lattices can be summarized as follows.

(a) Nitrogen occupies the octahedral voids in fcc lattices.
(b) A nitrogen or carbon atom in the octahedral void produces a symmetrical distortion in that it pushes away all six iron atoms.
(c) Although the radius of the nitrogen atom is smaller than that of the carbon atom, it dilates the lattice parameter more than does the carbon atom.
(d) The expression commonly used for the effect of nitrogen on the lattice parameters of austenitic stainless steels is $\delta = (1/X_N)\,(\Delta\,\alpha/\alpha)\,100$, where X_N denotes nitrogen in atomic per cent and α is the lattice parameter. The dilation factor, δ, is generally 0,20.
(e) The dilation of the lattice parameter in molybdenum-containing austenitic stainless steels is higher than that in molybdenum-free steels, because of the molybdenum's effect on the lattice parameter.

ELASTIC CONSTANTS

Austin and Ledbetter[5] established that the elastic constants (Young's modulus, shear modulus, and bulk modulus) decrease by 0,5 to 0,9 per cent per atomic per cent of added solute, while Poisson's ratio remains unaffected by carbon and nitrogen alloying. Byrnes *et al.*[6], on the other hand, found that the shear modulus and elastic modulus increase considerably with an increase in nitrogen content. The variation of the elastic modulus, *E*, with nitrogen content is shown in Figure 3. The results of Uggowitzer and Harzenmoser[7] show that the effect of nitrogen is minimal for 18 Cr–19 Mn steel. This illustrates that there is no general agreement among researchers regarding the effect of nitrogen on the elastic constants.

Table I
Development of process technologies for stainless steels high in nitrogen

Year	Process	Wt of ingot, kg
1960	Pressure-induction furnace Basic investigations	25
1965	Laboratory-scale pressure electroslag remelting Pressure plasma furnace	20 1000
1970	Pressure electroslag remelting	1000
1980	First production-scale pressure electroslag remelting	8000
1985	Pressure electroslag remelting	20000

Table II
Effect of nitrogen and carbon on lattice parameters

Alloy*	Effect of nitrogen (and/or carbon) on lattice parameter of fcc Fe–Cr–Ni alloys	Reference
Fe–18Cr–10Ni Max.% N = 0,709 Max.% C = 0,4	Linear increase in the lattice parameter with nitrogen and carbon content. Effect of nitrogen is greater than that of carbon.	8
25Cr–28Ni Max.% N = 0,397 25Cr–28Ni–2Mo Max.% N = 0,578	Relationships between lattice parameter and concentration of nitrogen are as follows: $\alpha = 3,5877 + 0,0288\%N$ $\alpha = 3,5932 + 0,0286\%N$. The lattice dilation of Fe–Cr–Ni steels by dissolved nitrogen is slightly smaller than that by dissolved carbon.	9
18Cr–10Ni–8Mn Max.% N = 0,45	Nitrogen increases lattice parameter linearly.	10
X5MnCrN19 13† X2CrNiN23 15† X3CrMnNiMoN20 6 43† X3CrNiMoN20 16 73†	Solid-solution strengthening of the austenitic steels by dissolved nitrogen is proportional to the change in lattice parameter of the austenitic matrix caused by the nitrogen.	11
18–20Cr–10Ni Max.% N = 0,24 Max.% C = 0,094 18Cr–8–16Ni Max.% N = 0,277 Max.% C = 0,028	Three linear equations were determined: When C and N are not separated, $\alpha = 0,3586 + 0,000854x_{C+N}$ $\alpha = 0,35866 + 0,000783 \cdot x_c + 0,000816 \cdot x_N$; when carbon is almost constant and low, $\alpha = 0,35864 + 0.000828 \cdot x_{C+N}$. Even though a nitrogen atom is smaller than a carbon atom, it dilates the lattice parameters more.	5

* The lattice parameters are given in ångstrom (Å)
† The compositions of these steels are as given in reference 11

MECHANICAL PROPERTIES

Strength

The mechanical properties of austenitic stainless steels improve with nitrogen additions[2]. Table III shows the effect of nitrogen on the yield strength of different types of austenitic stainless steels at different temperatures. The increase in yield strength is strongly temperature-dependent, and is about 500 MPa per wt % nitrogen at room temperature, while at 4 K it is 2500 MPa per wt % nitrogen.

Various empirical equations have been established by regression analysis relating strength to nitrogen concentration in the steel. Two popular equations have been proposed by Irvine *et al.*[12] and Norström[13]. The formers' equation can be used for the calculation of the 0,2 per cent proof strength of different types of stainless steels:

$$\sigma_{0,2} = 15,4\ \{4,4 + 23(C) + 1,3(Si) + 0,24(Cr) + 0,94(Mo) + 1,2(V) + 0,29(W) + 2,6(Nb) + 1,7(Ti) + 0,82(Al) + 32(N) + 0,16\ (\delta\text{-ferrite}) + 0,46\left(\frac{1}{\sqrt{d}}\right)\}, \quad [1]$$

where all the elements are expressed in percentages by weight, δ-ferrite is the percentage of δ ferrite, d is the mean linear intercept (grain diameter) in millimetres, and the strength is given in megapascals.

Norström[13] has proposed a second equation for a specific type of austenitic steel, namely AISI 316L. The equation is used for the estimation of the 0,2 per cent proof strength as a function of temperature, grain size, and nitrogen content:

$$\sigma_{0,2} = 15 + \frac{33000}{T} + 65\left(\frac{1690 - T}{T}\right)\sqrt{wt\ \%N} + [7 + 78(wt\ \%\ N)]\frac{1}{\sqrt{d}}, \quad [2]$$

where T is the temperature in kelvin.

The applicability of both equations has been tested by Varin and Kurzydlowski[14], who found the following:

- Equation [1] does not include the effect of nitrogen on the k parameter of the Hall–Petch equation, which is constant while it changes with nitrogen concentration in equation [2].

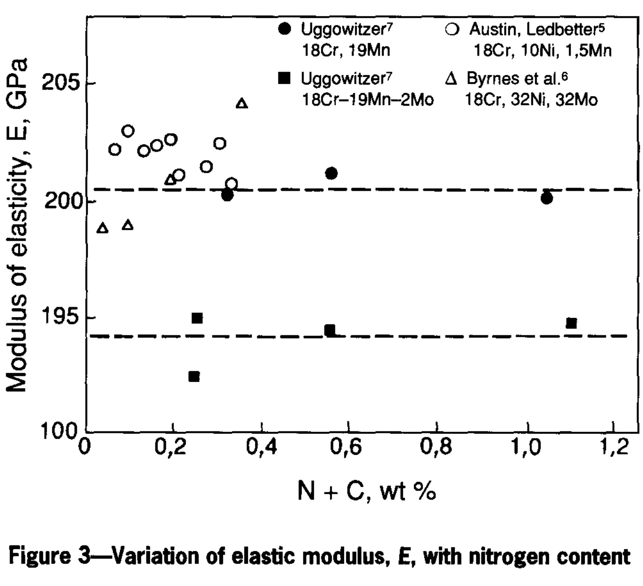

Figure 3—Variation of elastic modulus, *E*, with nitrogen content

Table III

Effect of nitrogen content on the yield strength of austenitic stainless steels

Base alloy	Temperature K	Increase in yield strength MPa / %N	Reference
Fe–Cr–Ni	4	2500	2
	4	3400	
	295	420	
	4	2910	
	4	3190	
Fe–18Cr–10Ni	295	440	
19Cr–10Ni	4	2400	
	295	500	
18–21Cr–10Ni	296	653	
	77	2400	
	296	620	
	473	440	
	673	160	
AISI 316	293	452	13
AISI 316L	293*	950	2
	573	640	
	873	540	
27Cr–32Ni–3Mo	78	1353	6
	194	607	
	296	409	
	523	340	
	673	314	
	873	305	
20Cr–15Ni–3Mo	295	710	2
27Cr–32Ni–3Mo*	296	498	10
	473	276	
	673	314	
	873	305	
Fe–Cr–Ni–Mo	4	2780	2
	295	690	
Fe–Cr–Mn	4	2140	
	295	680	
	295	580*	
	4	2940	15
	295	570	
	295	510	2
18Cr–10Ni–4Mn	293	510	10

* Grain size dependence also noticed

- The dependence of the yield strength on nitrogen concentration in equation [1] is linear, while its exponent is 1/2 in equation [2].
- Both equations have systematic errors in the estimation of the yield strength for commercial-type 316L steel.
- The value of k is under-estimated in equation [1], while equation [2] slightly over-estimates parameter k.

Varin and Kurzydlowski[14] also demonstrated that parameter k is not affected measurably by an increase in the number of coherent twin boundaries per grain. Therefore, the boundaries are not taken into account in the evaluation of the grain size of austenitic stainless steels.

It can be concluded from Table III that nitrogen has a beneficial effect on the yield strength of austenitic stainless steels. Equations [1] and [2], as well as the equations of other researchers, show that the exponent of the nitrogen content is unity or less than unity. Various concentrations of nitrogen have been obtained in steel by variation of the processing conditions. Processing under high nitrogen pressures and using powder-metallurgical and hot isostatic methods have produced very high concentrations of nitrogen in austenitic stainless steels. However, the ultimate nitrogen content is not known and has probably never yet been achieved[2]. High-nitrogen steels, often referred to as super-nitrogen steels, have been produced with yield strengths in the as-cast condition of about 1000 MPa at room temperature[2].

The effect of temperature on the yield strength of five austenitic stainless steels of different nitrogen contents is shown in Figure 4. It can be seen that, at temperatures above about 500 K, the yield strength does not change significantly with increasing temperature[6,16]. At temperatures below about 500 K, however, the yield strength changes dramatically with decreasing temperature. The slope for yield strength versus temperature increases with decreasing temperature and increasing nitrogen content. It is evident, therefore, that the yield strength of austenitic stainless steels varies with nitrogen content and temperature below 500 K. The alloys contained chromium (about 26,5 per cent), nickel (about 32 per cent), and carbon (between 0,013 and 0,020 per cent).

Irvine *et al.*[12], Norström[13], and Sandström and Bergquist[17] demonstrated that the k parameter of the Hall–Petch equation increased considerably as a result of alloying with nitrogen. The effect of grain size on strengthening is less pronounced in austenitic stainless steels than in ferritic carbon steels[13]. The value of k in ferritic carbon steels is high (23 N $mm^{-3/2}$), and these steels show significant increases in strength with decreasing ferrite grain size. In austenitic stainless steels, the value of k is low (7 to 8 N $mm^{-3/2}$) and the influence of grain size on yield strength is limited. The effect of nitrogen on k is illustrated in Figure 5, which shows that k increases by a factor of 2,5 when the nitrogen content of AISI 316L is raised from 0,02 to 0,27 per cent.

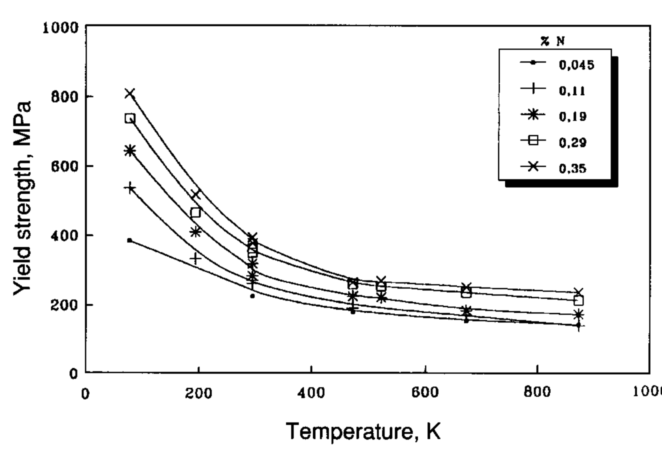

Figure 4—Variation of yield strength with temperature and concentration of nitrogen[6,16]

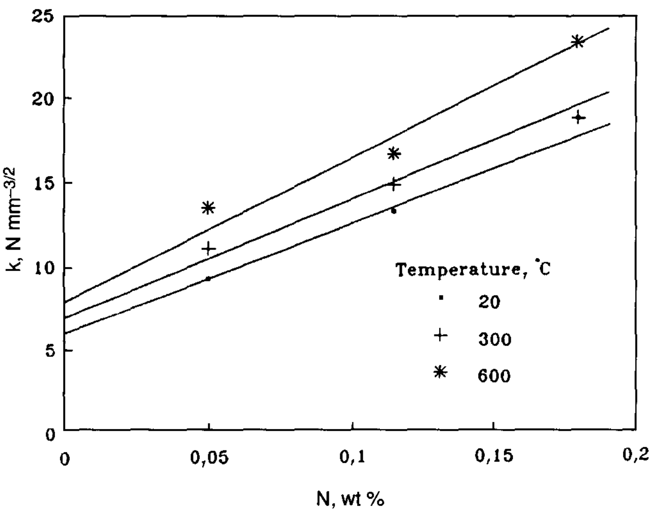

Figure 5—Variation of *k* with nitrogen content at three different temperatures[13]

As a consequence of the strong influence of nitrogen, relatively high yield strengths can be obtained in the annealed condition by a combination of nitrogen alloying and grain refinement.

Models dealing with the strengthening effects of nitrogen have been presented by several researchers. These models generally rely on the elastic theory and stacking-fault energy.

Ductility

Several authors have reported that the ductility of nitrogen-alloyed austenitic stainless steels is higher than that of nitrogen-free steels[10,18,19]. These findings were based on the results of tensile and Charpy impact tests. In addition, Speidel[19] has reported that solid-solution hardening does not reduce fracture toughness markedly (Figure 6), and that cold work can increase the yield strength further, although a moderate reduction in fracture toughness occurs.

Figure 7 shows that austenitic stainless steels of high nitrogen content in solid solution may constitute the one group of steels available with the highest product of strength and toughness.

Microstructure

Nitrogen affects the microstructure in two ways. Firstly, the stability of austenite increases so that its transformation to martensite during cold working is retarded[2]. Sandström and Bergquist[17] found that the amount of martensite produced for a specific amount of deformation was reduced. The second effect is that the dislocation structure has a tendency to change from cells to planar arrays with an increase in the amount of nitrogen[2,17,20–22]. The origin of this effect is not known with certainty, but it is possible that the energy of the stacking fault changes with variations in nitrogen content. Douglass *et al.*[22] found that, in Fe–20Cr–20Ni and Fe–20Cr–40Ni alloys particularly if nitrogen is present, the dislocations are arranged in coplanar groups, even though measurements of the stacking-fault energy indicate that dislocation tangling and cell substructures should be expected.

In fcc metals, a dislocation can be separated or 'extended' into two partial dislocations with a stacking fault between them. If the energy per unit area of a stacking fault is low, the separation between the partial dislocations is large. This

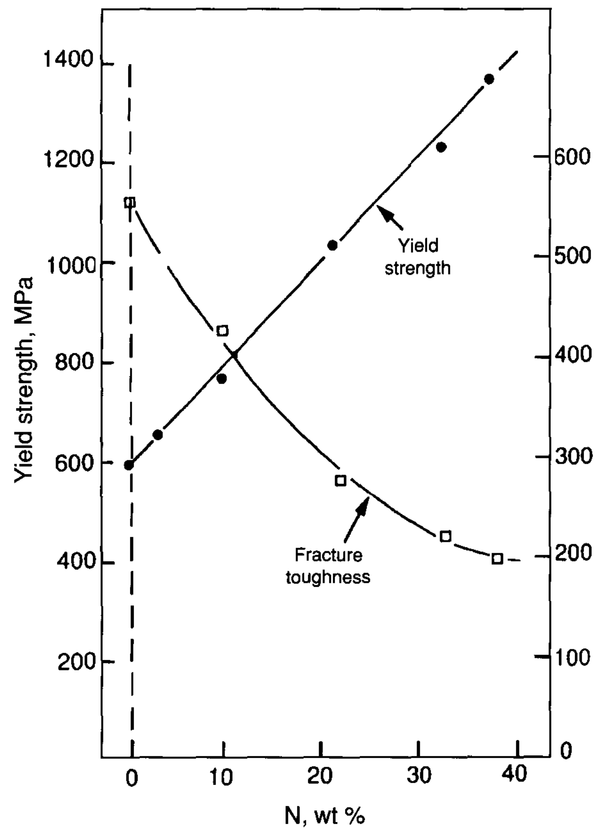

Figure 6—Effect of nitrogen on yield strength and fracture toughness[19]

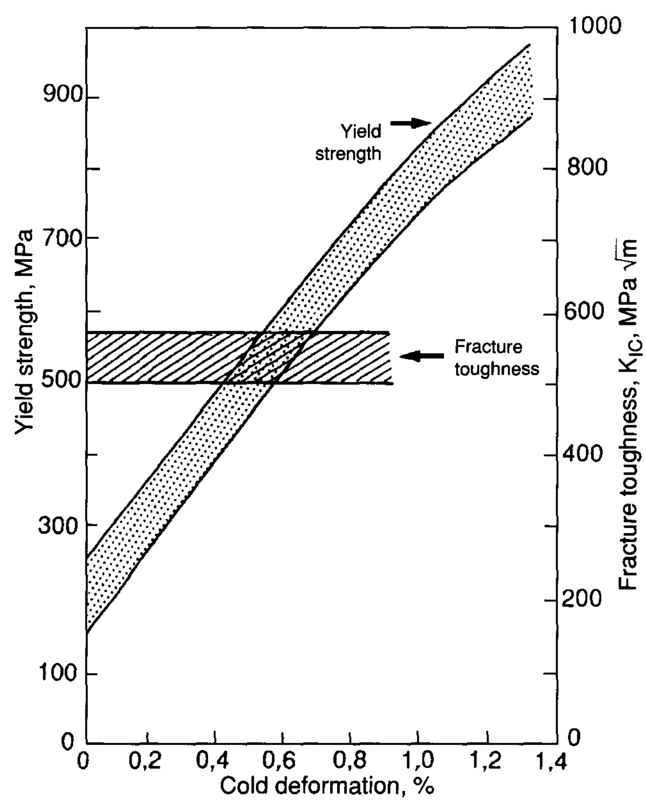

Figure 7—Effect of cold work on the yield strength and fracture toughness of a high-nitrogen austenitic stainless steel[13]

is important to the consideration of cross-slip onto an intersecting plane.

An extended screw dislocation can cross-slip only if some part of its length first contracts to form an unextended dislocation that requires an activation energy. A decrease in stacking-fault energy increases the distance between the partial dislocations and also the difficulty in combining them again. This increases the activation energy for cross-slip. Thus, materials with a lower stacking-fault energy are less likely to exhibit cross-slip. However, the re-combination of partial dislocations is aided by thermal activation, and the ability to cross-slip therefore increases with increasing temperature.

The effect of nitrogen on the stacking-fault energy of Fe–Cr–Ni alloys is not clear. Table IV, a summary of the known effects of nitrogen on stacking-fault energies for Fe–Cr–Ni and Fe–Cr–Ni–Mn alloys, indicates the following.

(a) Stacking-fault energy is independent of nitrogen content in Fe–Cr–Ni alloys.
(b) In Fe–Cr–Ni–Mn alloys, there is a transition in stacking-fault energy with an increase in nitrogen content.
(c) It is possible that there is also a transition in stacking-fault energy in Fe–Cr–Ni alloys but at higher nitrogen contents.

The aging behaviour of nitrogen-alloyed austenitic stainless steels has been studied by several researchers. It has been shown that a cellular type of precipitation occurs in austenitic stainless steels when alloys of a certain nitrogen concentration are aged in a certain temperature range[24-26]. The cellular precipitation is in the form of alternating layers of austenite and Cr_2N. The amount of nitrogen in the austenite of the cellular constituent is different from that in the matrix austenite. The amount of nitrogen in the untransformed matrix and cellular precipitate was determined by means of electron-microprobe micro-analyses. It was found that, for 25Cr–20Ni steel with a nitrogen content of 0,59 per cent, the amount of nitrogen in the untransformed austenite matrix and the cellular constituent was 0,33 and 1,07 per cent respectively. It was also found that there was no significant concentration gradient of nitrogen in the untransformed matrix of the aged specimens. The conditions for the precipitation of the cellular constituents are summarized in Table V.

Table IV
Effect of nitrogen on the stacking-fault energies of austenitic stainless steels

Base alloy	Stacking-fault energy, mJ/m^2	Reference
Fe–21Cr–6Ni–9Mn	Decrease from 53 mJ/m^2 at 0,21 wt % N to 33 mJ/m^2 at 0,24 wt % N. No further decrease up to 0,52 wt % N.	21
Fe–18Cr–10Ni–8Mn	For nitrogen content of 0 to 0,14%. Decreases with increasing N up to 0,14%.	10
18Cr–10Ni	Decreases	10
18Cr–10Ni	No change	10
10–30Cr, 10–30Ni	No change	10
20Cr–20Ni	No change	10
17–25Cr, 8–19Ni	Decreases according to the equation $\gamma = 94+1{,}4\%Ni-1{,}1\%Cr-77\%N$.	30
18Cr–10Ni	C+N $\leq$ 0,36 wt %, N $\leq$ 0,26 wt % no change.	2
17Cr–12Ni–2Mo	No change	2

The growth characteristics of the cellular precipitate of Cr_2N in Cr–Ni austenitic stainless steels were studied by Kajihara *et al.*[27]. They found that the migration rate of cell boundaries decreased with the reaction time. The nitrogen content averaged over the entire cell containing Cr_2N precipitates and austenitic matrix was higher than that of the matrix. In addition, they found that the nitrogen content of the austenite in the cellular regions was higher than that of the matrix austenite. The nitrogen content of the untransformed matrix decreased with the growth of the cellular constituent.

Creep and Fatigue

The service life of austenitic stainless steels in high-temperature applications is prolonged by nitrogen additions[2]. The controlled addition of nitrogen to both AISI types 304 and 316 stainless steels increases the creep and rupture strengths at 650°C (Figure 8). Several researchers have reported that nitrogen is an efficient creep strengthener of austenitic stainless steels in the temperature range 400 to 600°C. Solberg[28] tested AISI 316 in the temperature interval 700 to 900°C, and demonstrated that, below 800°C, nitrogen-bearing steel is stronger, while the traditional carbon-containing alloy exhibited a better creep resistance at 900°C. He pointed out that the strengthening effect of nitrogen decreases with increasing temperature. Kawabe *et al.*[29] found that nitrogen in combination with molybdenum produces a greater improvement in creep rupture strength than the sum of the individual contributions.

It is well known that fcc metals, in which a decrease in stacking-fault energy promotes the formation of planar slip (planar array of dislocations), and alloys exhibiting planar dislocations are more fatigue-resistant than alloys in which wavy slip predominates[20]. The effect of nitrogen on the stacking-fault energy of austenitic stainless steels is not

Table V
Conditions for the cellular type of precipitation in austenitic alloys

Type	Characteristic of cellular precipitation	Reference
20Cr–17Mn	The material was aged in a temperature range of 400 to 800°C. Cellular precipitation was observed at the higher temperatures. The alloy contained 0,6 wt % N.	25
25Cr–20Ni	A model derived for cellular precipitation at a temperature of 805°C. The alloy contained 0,42 to 0,50 wt % N.	26
Nitronic 50	Cellular precipitation was observed on samples with 0,68 wt % N and in a temperature range of 700 to 1000°C.	24

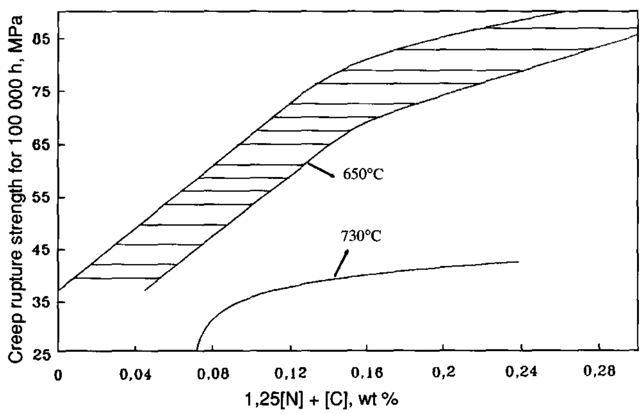

Figure 8—Effect of nitrogen on creep

well known but, as discussed earlier, nitrogen changes the arrangement of dislocations from cells to planar arrays.

Nilson[20] demonstrated that nitrogen-alloyed austenitic stainless steels have a fatigue resistance that is twice as high as that of AISI 316. He proposed that the difference is accompanied by apparent dissimilarities in terms of slip behaviour. Degallaix *et al.*[31] also compared the fatigue life of an austenitic nitrogen-containing steel (21Cr–9Ni–3Mo–4Mn) with that of AISI 316, and reported that the fatigue life of the nitrogen-containing steel increased with increasing nitrogen up to a nitrogen content of 0,12 per cent. However, no further increase was obtained from nitrogen contents of up to 0,39 per cent. On the other hand, Mineura and Ishizaki[32] found that nitrogen increased the fatigue strength and fatigue life of a 20Cr–10Ni steel, even at concentrations of 0,7 per cent. It appears that the increase in fatigue resistance is due to increased resistance to strain localization as a result of increased planar slip. Dhers *et al.*[33], in studies of the rates of crack growth in AISI 316 steel at low and high nitrogen levels, showed that nitrogen decreases the crack growth at high ΔK values (Figure 9). This result was related to the effect of nitrogen on the crack-opening displacement.

EFFECT OF NITROGEN ON CORROSION

The effect of nitrogen on the corrosion resistance of austenitic stainless steels was reviewed by Powel[34] and, more recently, by Truman[35]. They report that the effect of nitrogen varied with the type of corrosion and the type of austenitic stainless steel. Results in the literature show that nitrogen contents below approximately 0,20 per cent decrease the susceptibility of austenitic stainless steels to intergranular corrosion. Brian[36] has demonstrated that nitrogen additions improve grain-boundary corrosion resistance by retarding carbide precipitation and chromium depletion. He comments that this is due to the rapid diffusion of nitrogen to the grain boundaries and to its presence at grain boundaries during carbide precipitation[36]. At the grain boundaries, nitrogen reacts with chromium to form Cr_2N particles, which tends to deplete the area around these particles of chromium. However, the chromium depletion appears not to be as severe as that obtained when $Cr_{23}C_6$ forms by reaction between chromium and carbon. It can be concluded that nitrogen additions (at least within some limits) reduce the susceptibility to sensitization and intergranular corrosion of austenitic stainless steel.

Figure 10 illustrates that alloying with nitrogen increases resistance to acid corrosion and pitting corrosion[2]. The tests on AISI 304 steel in acidified ferric chloride and 20 per cent sodium chloride showed that pitting frequency and weight loss decrease with increasing nitrogen content[2]. However, Truman[35] reported recently that the amount of information on the effect of nitrogen on corrosion resistance in acids is limited, and that a clear picture in this regard cannot be drawn.

The effect of nitrogen on stress–corrosion cracking has not been studied extensively[22]. However, most of the results available indicate that nitrogen increases a steel's susceptibility to stress–corrosion cracking[22].

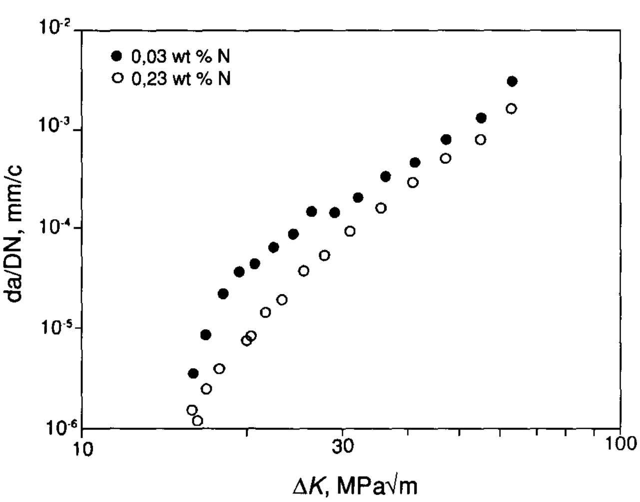

Figure 9—Effect of nitrogen on the rate of crack growth in AISI 316 steel[33]

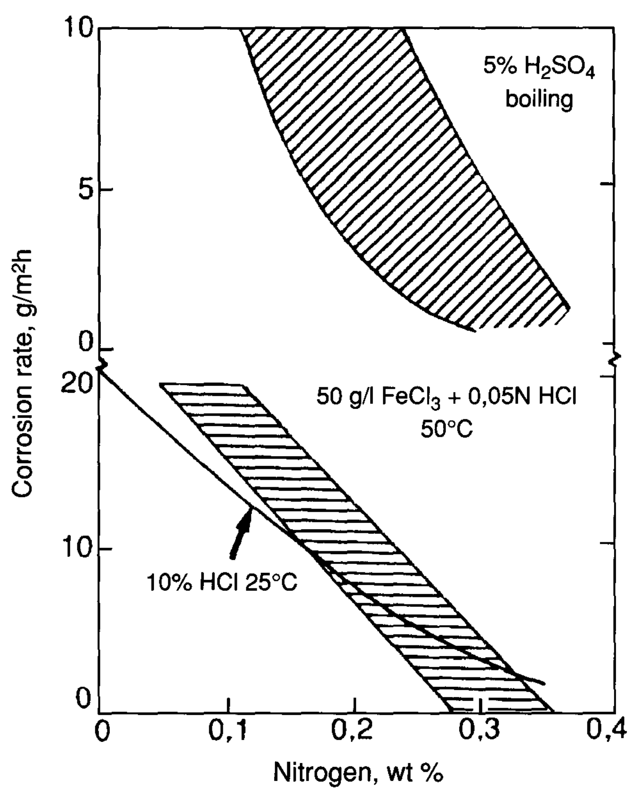

Figure 10—Dependence of corrosion rate on nitrogen content

SUMMARY

The significant findings of earlier researchers in this field can be summarized as follows.

(1) Nitrogen is a strong austenite stabilizer.
(2) The solubility of nitrogen in austenite is higher than that of carbon.
(3) Nitrogen is an effective strengthening element at room, at elevated, and at cryogenic temperatures.
(4) Nitrogen increases both the strength and the ductility of austenitic stainless steels.
(5) The service life of austenitic stainless-steel components at high temperatures is prolonged by nitrogen additions, although there is no consensus among researchers.
(6) The fatigue life of nitrogen-alloyed steels increases with increasing nitrogen content.
(7) The corrosion resistance of nitrogen-alloyed austenitic stainless steels varies with the type of corrosion and the type of steel.

It is evident that a considerable amount of research has been carried out on the influence of nitrogen on the structure and properties of austenitic stainless steels. However, no information could be found on the influence of nitrogen on the properties of steel type AISI 310S.

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