Communications

Room-Temperature Elastic Constants and Low-Temperature Sound Velocities for Six Nitrogen-Alloyed Austenitic Stainless Steels

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Despite large chemical-composition differences, six nitrogen-alloyed stainless steels show only slight differences in their room-temperature elastic constants, determined by ultrasonic-velocity measurements. At low temperatures, magnetic transitions cause anomalous elastic-constant behavior and significant differences in elastic constants. Nitrogen content seems not to affect the elastic constants.

Metallurgists began studying nitrogen-alloyed stainless steels in 1925.[1] Renewed interest in these alloys results from two causes: concern over diminishing supplies of alloying elements such as nickel and the unfulfilled dream of a high-strength fcc steel.

Research on these alloys has been largely empirical and without theoretical guidance. These studies, which focused mainly on mechanical-strength properties have been reviewed by several authors.[1-3]

One small but important step toward a basic understanding of a material is knowledge of its elastic constants, which are among the most fundamental mechanical properties. Effects of nitrogen on the elastic constants of these alloys remain unstudied. Nor have such effects been investigated for the relevant binary systems. Furthermore, the effects of Cr, Ni, and Mn contents on the elastic constants of these stainless steels remains unresolved. Another uncertainty is the occurrence of low-temperature magnetic transitions, or possibly even structural transitions, that manifest themselves as elastic-constant anomalies.

The presently reported study does not resolve these questions, but contributes significantly toward their solution by providing accurate measurements of basic properties of several alloys. The complete set of elastic constants—Young's modulus, shear modulus, bulk modulus, and Poisson's ratio—were determined at ambient temperature for six nitrogen-alloyed stainless steels representing a wide range of chemical compositions. One of the elastic constants, the longitudinal modulus, was determined during cooling to either liquid-nitrogen or liquid-helium temperature.

Ledbetter and Collings[4] recently reported elastic constants of three nitrogen-alloyed steels—Fe-18Cr-3Ni-12Mn, Fe-21Cr-6Ni-9Mn, and Fe-22Cr-13Ni-5Mn—between room temperature and liquid-nitrogen temperature. All these alloys undergo Néel (paramagnetic-antiferromagnetic) transitions at a below-ambient temperature, T_N, that depends mainly on the Mn content. All the elastic constants—Young's modulus, shear modulus, bulk modulus, Poisson's ratio, and so forth—behave anomalously at temperatures near T_N. Higher Mn content causes a higher T_N and a larger elastic-constant change at T_N.

This communication reports results for three additional nitrogen-alloyed steels—Fe-18Cr-2Ni-13Mn, Fe-17Cr-9Ni-8Mn, and Fe-18Cr-8Ni (AISI 304N), whose chemical compositions are given in Table I and metallurgical characterizations in Table II. Note that all six steels were in a solution-treated-and-quenched state; thus, most or all nitrogen was presumably in interstitial solid solution and not in precipitates. Reference 4 and references therein describe the experimental equipment and methods.

Table III gives the room-temperature sound-velocity and elastic-constant results. Excluding the Fe-17Cr-9Ni-8Mn alloy, Young's modulus varies least (±1.3 pct) and the bulk modulus varies most (±2.4 pct). Considering the chemical-composition differences among the alloys, these are surprisingly small variations. The slower shear-wave velocity for Fe-17Cr-9Ni-8Mn, which results in lower Young's and shear moduli and in higher bulk modulus and Poisson's ratio, is not understood. Strong texture resulting in higher elastic anisotropy may explain this result. But elastic anisotropy measured in Fe-18Cr-3Ni-12Mn amounted to only 0.16 and 0.32 pct for the longitudinal and shear velocities measured in three orthogonal directions.[5] This alloy's high Si content may cause its relatively low shear

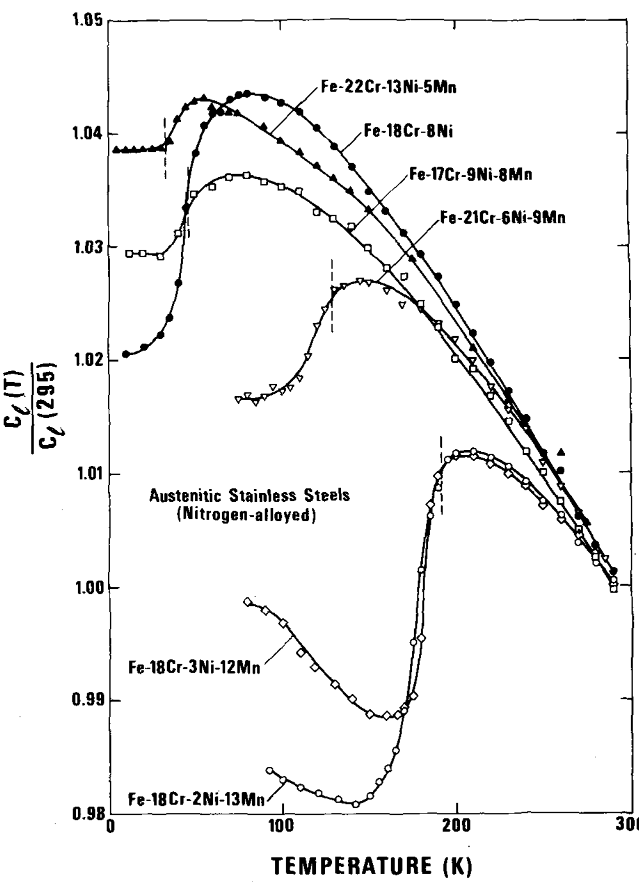

Fig. 1—Temperature dependence of the longitudinal modulus ρv_l^2 for six nitrogen-alloyed stainless steels. As described in the text, the anomalies are due to Néel (paramagnetic-antiferromagnetic) transitions.

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Table I. Chemical Compositions (Supplier's Analysis) of Studied Alloys, Weight Percent

	Cr	Ni	Mn	N	C	P	S	Si	H	O	Fe
Fe-18Cr-2Ni-13Mn	18.00	1.57	11.88	0.34	0.100	0.027	0.008	0.60	—	—	Balance
Fe-18Cr-3Ni-12Mn	18.09	3.26	13.22	0.37	0.038	0.023	0.005	0.52	—	—	Balance
Fe-18Cr-3Ni-12Mn*	18.0	3.21	13.85	0.425	0.042	—	—	—	0.00008	0.00465	Balance
Fe-21Cr-6Ni-9Mn	20.93	6.8	8.92	0.24	0.050	0.021	0.007	0.36	—	—	Balance
Fe-22Cr-13Ni-5Mn†	21.15	12.37	4.96	0.310	0.041	0.026	0.015	0.49	—	—	Balance
Fe-17Cr-9Ni-8Mn	16.85	8.62	8.43	0.12	0.071	0.027	0.005	4.00	—	—	Balance
Fe-18Cr-8Ni‡	18.65	9.49	1.88	0.12	0.048	0.019	0.024	0.38	—	—	Balance

* Westinghouse Research and Development Center analysis.
† Also contains 2.17 Mo, 0.18 Nb, and 0.15 V.
‡ Also contains 0.07 Cu, 0.06 Co, 0.52 Mo, and 0.03 V.

Table II. Metallurgical Characterization of Studied Alloys

	Density, g/cm^3	Grain Size, ASTM No.	Hardness, R_b	Form	Condition
Fe-18Cr-2Ni-13Mn	7.734			3 cm bar	Commerical heat treatment
Fe-18Cr-3Ni-12Mn	7.817	6	92		Annealed 1066 °C for 1 h, water quenched
Fe-21Cr-6Ni-9Mn	7.838	2.5	106	1.8 cm bar	Commercial heat treatment
Fe-22Cr-13Ni-5Mn	7.884	7	98	5 cm plate	Annealed 1080 °C for 1 h, water quenched
Fe-17Cr-9Ni-8Mn	7.594			2.5 cm bar	Commerical heat treatment
Fe-18Cr-8Ni	7.860	3	79	5 cm wall, 1 m diam tube	Annealed 1052 °C for 2.5 h, water quenched

Table III. Room-Temperature Sound Velocities and Elastic Constants of Six Nitrogen-Alloyed Stainless Steels

	Fe-18Cr-2Ni-13Mn	Fe-18Cr-3Ni-12Mn	Fe-21Cr-6Ni-9Mn	Fe-22Cr-13Ni-5Mn	Fe-17Cr-9Ni-9Mn	Fe-18Cr-8Ni
Long. Velocity, cm/μs	0.5733	0.5633	0.5686	0.5727	0.5727	0.5760
Transv. Velocity, cm/μs	0.3112	0.3104	0.3104	0.3089	0.2941	0.3152
Long. Modulus, 10^{11} N/m^2	2.542	2.480	2.534	2.586	2.491	2.608
Shear Modulus, 10^{11} N/m^2	0.749	0.753	0.755	0.752	0.657	0.781
Bulk Modulus, 10^{11} N/m^2	1.543	1.476	1.527	1.583	1.615	1.567
Young's Modulus, 10^{11} N/m^2	1.934	1.931	1.945	1.948	1.735	2.009
Poisson's Ratio	0.291	0.282	0.288	0.295	0.321	0.286

modulus, but apparently such factors remain unevaluated.

Longitudinal-modulus-*vs*-temperature curves shown in Fig. 1 reveal qualitatively similar behavior for all six alloys: a normal linear increase upon cooling below room temperature, an anomalous decrease through a minimum, and an increase to the zero-temperature value. The longitudinal modulus reflects changes that occur either in the bulk modulus or in the shear modulus. Néel (paramagnetic-antiferromagnetic) transition temperatures measured previously[4] for three alloys and computed empirically[6] for one alloy are also indicated as dashed vertical lines in Fig. 1. Clearly, the elastic-constant anomalies relate to the magnetic transitions. Based on the elastic data, Néel temperatures are approximately 171 K for Fe-18Cr-2Ni-13Mn and 43 K for Fe-17Cr-9Ni-8Mn.

In summary, six nitrogen-alloyed austenitic stainless steels, with one exception, show similar room-temperature elastic constants. During cooling all six steels undergo Néel (paramagnetic-antiferromagnetic) transitions accompanied by anomalous elastic-constant/temperature behavior. The transition temperature relates strongly to the Mn content. While further studies, with systematic nitrogen-content variations, are required, solid-solution nitrogen content seems not to influence the elastic constants of these alloys. The Fe-18Cr-3Ni-12Mn alloy was studied also in an annealed-and-furnace-cooled condition. The elastic constants were: Young's modulus = 1.965 · 10^{11} N/m^2, shear modulus = 0.768 · 10^{11} N/m^2, bulk modulus = 1.489 · 10^{11} N/m^2, and Poisson's ratio = 0.282. Thus, precipitation of nitrogen causes a one to three pct lowering of both the dilatation-type and shear-type elastic constants.

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REFERENCES

1. B. Gunia and G. R. Woodrow: *J. Mater.*, 1970, vol. 5, pp. 413–30.
2. K. J. Irvine, T. Gladman, and F. B. Pickering: *J. Iron Steel Inst.*, 1969, vol. 207, pp. 1017–28.
3. A. Randak, W. Wessling, H. E. Beck, H. Steinmauer, and L. Faust: *Stahl Eisen*, 1971, vol. 91, pp. 1255–70.
4. H. M. Ledbetter and E. W. Collings: *Metal Science of Stainless Steels*, pp. 22–40, TMS—AIME, New York, 1979.
5. H. M. Ledbetter and E. W. Collings: Unpublished research.
6. L. A. A. Warnes and H. W. King: *Cryogenics*, 1976, vol. 16, pp. 659–67.

Fatigue Strength of TRIP Steels

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Studies[1–6] of the fatigue behavior of metastable austenitic steels have shown interesting differences between the behavior of high strength TRIP steels[7] and that of lower-strength metastable austenites, while identifying a marked contrast between the influence of the deformation-induced martensitic transformation under strain-control *vs* stress-control conditions. Fatigue crack propagation (FCP) studies (controlled ΔK) have indicated that the deformation-induced transformation retards crack propagation in the lower strength austenites, particularly at low ΔK,[1] and also exerts a beneficial influence in high strength TRIP steels, though to a much lesser extent.[2] In smooth bar fatigue tests on lower strength austenites, the transformation was found to reduce fatigue life under conditions of controlled plastic strain amplitude.[3] Under controlled *total* strain amplitude, the transformation was found to be detrimental to low cycle fatigue life, but it was indicated that a small amount of transformation may be beneficial at high cycles.[4] Similarly, the low cycle fatigue properties of high-strength TRIP steels were found to be degraded by the deformation-induced transformation under controlled total strain amplitude conditions.[5] Under *stress*-control, however, the fatigue life of the lower strength metastable austenites is found to be greatly enhanced by the transformation; for smooth bar tests with a stress ratio of $R = 0$, fatigue limits in excess of the yield strength have been reported.[6] The above trends are summarized in Table I, with the lengths of the arrows used to give some qualitative indication of the changes. This study was undertaken to extend the stress-control fatigue tests to the high-strength TRIP steels and determine whether the beneficial effect of the deformation-induced transformation persists to the high strength levels. In addition, fatigue data generated under stress-control conditions may provide a more useful design criterion for many applications.

In a previous study,[8,9] both air and vacuum melts were prepared of a TRIP steel of nominal composition: Fe-9 Cr-8 Ni-4 Mo-2 Mn-2 Si-0.3 C. Solution-treated austenitic billets were strengthened by warm-extrusion to reductions of area of 40, 60, or 80 pct in the temperature range 400 to 850 °F (480 to 730 K). Melt compositions and processing details are given in Refs. 8 and 9. Preliminary room-temperature tensile tests revealed that the as-extruded material was too stable with respect to martensitic transformation during testing, resulting in lower than expected values of uniform elongation. A tempering treatment designed to alter the austenite matrix composition through carbide precipitation was found to restore the correct austenite stability for optimum room-temperature tensile properties. A 1 h temper at 1100 °F (870 K) produced a markedly increased uniform elongation and a higher ultimate tensile strength. The overall tensile properties of the extruded and tempered material were superior to those of warm-rolled material; the tensile results are discussed in detail in Ref. 9 and summarized in Table II. In the current study, fatigue properties of both the as-extruded and the tempered material were examined to compare materials of differing stability, thus allowing an assessment of the influence of the deformation-induced transformation.

Load controlled uniaxial high cycle fatigue tests were conducted at room temperature on an SF-10U Satec fatigue machine at a frequency of 30 Hz and R ($\sigma_{min}/\sigma_{max}$) ratio of 0.1. Cylindrical smooth fatigue specimens having a minimum diameter of 0.200 in. (0.508 cm) at the center of a slightly tapered gage section were used. The specimen threads were grit-blasted to eliminate thread fatigue failures during testing.

Figures 1, 2, and 3 show the S-N curves (maximum stress *vs* number of cycles to failure) for the materials extruded to reductions of 40, 60 and 80 pct, respectively. Each figure shows the curves for both the as-extruded and tempered materials. Both vacuum and air-melted materials were tested in the as-extruded

Table I. Effect of Strain Induced $\gamma \rightarrow \alpha'$ Transformation on Fatigue Properties

	Test Condition	Lower Strength Austenites, $\sigma_y < 60$ ksi	High Strength TRIP Steels, $\sigma_y > 200$ ksi
Strain control	LCF ($\Delta\epsilon_T$)	↓ (↑ high N_f?)	↓
	LCF ($\Delta\epsilon_p$)	↓	
Stress control	da/dN *vs* ΔK	↑	↑
	HCF	↑	?

LCF—low cycle fatigue, HCF—high cycle fatigue, $\Delta\epsilon_T$—total strain range control, $\Delta\epsilon_p$—plastic strain range control, N_f—Number of reversals to failure, da/dN—crack growth rate, ΔK—stress intensity range.

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