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Comparing the Formability of AISI 304 and AISI 202 Stainless Steels

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The formability of AISI 202 austenitic stainless steel was compared with that of type AISI 304 stainless steel. Type 202 is a low-nickel austenitic stainless steel alloyed with manganese and nitrogen. In this study, the formability of the two grades was examined using Erichsen cupping tests and room temperature uniaxial tensile tests performed at various angles to the rolling direction. AISI 202 appears to work-harden at a slightly higher rate than AISI 304, even though the austenite in type 202 is more stable than that in 304 with respect to the formation of deformation-induced α′ martensite. Although both grades are predicted to be susceptible to earing during deep drawing, AISI 202 displays a higher work-hardening exponent, higher average normal anisotropy, and a higher limiting drawing ratio than AISI 304. Similar cup heights were measured during Erichsen cupping tests, confirming that the two grades have very similar deep drawing properties. The results of this investigation therefore suggest that AISI 202 is a suitable alternative for AISI 304 in applications requiring good deep drawing properties.

Keywords mechanical testing, shaping, stainless steels

1. Introduction

Most austenitic stainless steels produced today are of the AISI 304 variety, containing approximately 18% chromium and 8% nickel. The price of nickel tends to be variable and occasionally peaks at very high levels. An incentive therefore exists to produce a stainless steel with properties similar to those of AISI 304, but with less expensive elements, substituting all or part of the nickel.

The primary function of nickel in austenitic stainless steels is to ensure that the steel remains austenitic down to room temperature. Nickel is both an excellent austenite-former (it enlarges the austenite phase field at elevated temperatures at the expense of ferrite) (Ref 1) and an austenite-stabilizer (it stabilizes the austenite against martensite formation by lowering the M_s-temperature) (Ref 2). Nitrogen is a very effective substitute for nickel in stainless steels because at acts as both an excellent austenite-former and austenite-stabilizer (Ref 1). Unfortunately, all the nickel cannot be replaced by nitrogen because of the limited solubility of nitrogen in iron alloys. Manganese is known to increase the solubility of nitrogen in steel, and this constitutes the main reason for adding significant amounts of manganese as an alloying element to nitrogen-alloyed stainless steels (Ref 3).

The AISI 200-series stainless steels are well-known examples of low-nickel austenitic stainless steels alloyed with manganese and nitrogen. In these steels, about half the nickel in the Cr-Ni AISI 300-series steels is replaced with manganese and nitrogen. The 200-series stainless steels were initially developed to address a shortage of nickel in times of national emergency. Initiated during World War II and continued throughout the Korean War, development work covering the substitution of manganese and nitrogen for nickel in austenitic stainless steels led to the production of grades AISI 201 and 202, the most widely used chromium-nickel-manganese austenitic stainless steels available today. Owing to the lower nickel contents of these alloys, the rate of work-hardening and the strength of the 200-series steels tend to be higher than those of comparable 300-series steels (Ref 2). This increase in strength and hardness does not reduce the ductility significantly, and in some applications, the higher strength may be advantageous. Type 201 is considered to be a satisfactory substitute for AISI 301 where machinability and severe forming characteristics are not essential. In applications where formability is important, type 202 is more preferred because of its lower rate of work-hardening. Although types 201 and 202 have somewhat lower resistance to chemical corrosion than 301 and 302, their resistance to atmospheric corrosion is comparable (Ref 4).

As described above, a possible drawback of steels alloyed with manganese and nitrogen as substitutes for nickel is a rapid rate of work-hardening on deformation. This rapid rate of work-hardening is attributed to the transformation of metastable austenite to strain-induced martensite on deformation (Ref 5), and work-hardening of the austenite itself due to dislocation interactions.

In metastable austenitic stainless steels, two types of martensite can form on deformation: body-centered cubic (or tetragonal) α′ martensite, and hexagonal close-packed ε martensite (Ref 5). The εmartensite phase is often reported as a transition phase in the transformation of austenite to α′ martensite (Ref 6-8), as evidenced by the presence of εmartensite at low strains in type 304 stainless steel. This ε martensite transforms completely to α′ martensite as the level of deformation increases (Ref 6, 9).

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The higher rate of work-hardening associated with the partial transformation of austenite to deformation-induced martensite during forming may be beneficial during deep drawing because of a delay in the onset of necking (Ref 10). However, the formation of martensite during deep drawing introduces a requirement for annealing during and after multistage deep drawing to reduce the required working force, magnetization, and susceptibility to delayed cracking.

The rate of work-hardening in austenitic stainless steels is also a function of the stacking fault energy (SFE) of the alloy. Higher nickel contents raise the SFE, leading to lower rates of work-hardening (Ref 2, 10).Nitrogen is reported to decrease the SFE of austenitic stainless steels, but only if present in amounts of approximately 0.20% (wt.%) or higher (Ref 11). Although the nitrogen contents of the 200-series stainless steels are normally below 0.20%, the lower nickel contents (compared to type 304) are expected to reduce the SFE and result in higher rates of work-hardening, even in the absence of strain-induced martensite.

Type 304 stainless steel is widely used in forming applications because of its superior formability. The high nickel price in recent years prompted an investigation into the feasibility of replacing AISI 304 with AISI 202 in applications requiring formability and good deep drawing properties. The aim of this investigation was therefore to study the formability of AISI 202 stainless steel using uniaxial tensile tests and Erichsen cupping tests, and to compare the results with those obtained for AISI 304 under the same test conditions.

2. Experimental Procedure

Two grades of austenitic stainless steel, corresponding in composition to AISI 304 and AISI 202, were supplied in the form of fully annealed 0.7-mm-thick sheet. The chemical compositions of the two grades examined in this investigation are shown in Table 1.

Tensile test samples were machined from each alloy at angles of 0°, 45°, and 90° to the rolling direction. The samples were prepared according to the requirements of ASTM E8 M-04 for standard rectangular test specimens with a nominal width of 12.5 mm and a gauge length of 50 mm. Low strain rate uniaxial tensile tests were performed up to failure at an initial strain rate of 9.9×10^{-4} s^{-1} for each of the rolling directions. A series of interrupted tensile tests were also performed up to 40%, 30%, 20%, and 10% elongation, at an initial strain rate of 2.6×10^{-3} s^{-1}. All tests were performed at room temperature. Four samples were tested for each set of experimental conditions to ensure repeatability.

In order to quantify the volume fraction strain-induced α' martensite formed in each specimen, a calibrated Fischer Ferritscope™ was used for determining the ferrite number (FN) of the specimen. The FN was measured in the region of the fracture surface (for samples tested to fracture), or in the highest strain regions of samples subjected to interrupted tensile tests. A Ferritscope is normally used for correlating the ferrite content of austenitic stainless steel welds to the magnetic response of the sample (austenite is paramagnetic, and ferrite is ferromagnetic). This magnetic response is quantified as an arbitrary ferrite number. Although the measured ferrite number does not correlate directly with the percentage martensite, α' martensite is ferromagnetic and in the absence of significant amounts of ferrite, the measured FN should provide an indication of the presence of α' martensite in an austenitic sample. Already published equations can be used for estimating the martensite content from the measured ferrite number.

After tensile testing, hardness tests were performed using a calibrated Vickers hardness tester with an applied load of 3 kg. The hardness indentations were placed in the region of the fracture surface (for samples tested to fracture), or in the highest strain region of samples subjected to the interrupted tensile tests.

In order to quantify the deep drawability of the steels, Erichsen test samples were prepared according to the requirements of ASTM E643-84. The samples were tested using an Erichsen cupping test apparatus with petroleum jelly as lubricant. Three tests were performed for each alloy, and the average cup height was determined for both grades.

3. Results and Discussion

3.1 Hardness Measurements and the Formation of Strain-Induced Martensite

The average hardness is shown in Fig. 1 as a function of percentage applied strain for type 304 and type 202 stainless steels. The initial as-received hardness values were measured as 174 HV_3 (hardness on the Vickers scale with an applied load of 3 kg) and 182 HV_3 for grades 304 and 202, respectively. As expected, the hardness values of both alloys increase with increasing strain because of work-hardening. The results

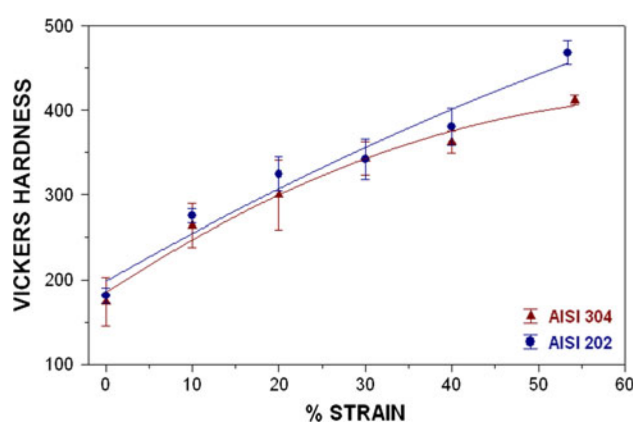

Fig. 1 Hardness as a function of percentage applied strain for the two alloys under investigation (with 95% confidence interval)

Table 1 Chemical compositions of the two alloys examined during the course of this investigation (wt.%, balance Fe)

Alloy	C	Cr	Mn	Cu	Ni	N	Si	Mo	S	P	B
AISI 304	0.040	18.27	1.19	0.07	8.65	0.038	0.49	0.088	0.002	0.026	0.003
AISI 202	0.048	16.10	7.40	1.64	4.04	0.106	0.40	0.194	0.001	0.027	0.003

suggest that AISI 202 work-hardens at a slightly faster rate than AISI 304, which may be due to the formation of higher levels of strain-induced martensite in AISI 202 on deformation, or a higher rate of work-hardening in the austenite itself. This is examined in more detail in this section.

To determine whether AISI 202 is more prone to the formation of strain-induced martensite, the formation of martensite on deformation was studied by measuring the ferrite number (FN) for various amounts of applied strain. In the as-received condition, type 304 had an average ferrite number of 0.1 (suggesting the presence of a small amount of retained δ-ferrite), whereas a ferrite number of 0 was measured for type 202. This indicates that the samples were largely austenitic in the annealed condition, with almost no ferrite or martensite in the as-supplied condition. Since the ferrite content of the alloys is unlikely to increase on room temperature deformation, any increase in FN with applied strain is indicative of the formation of strain-induced α′ martensite on deformation.

As shown in Fig. 2, the FNs of both grades of stainless steel remain constant up to an applied strain of approximately 20%. At higher levels of applied strain, the FN of type 304 increases rapidly up to an average FN of 5.8 at fracture. Superimposed on Fig. 2 is the percentage martensite measured as a function of applied strain for type 304 (Ref 12). Examination of both curves for type 304 suggests that this alloy contains approximately 25% α′ martensite at fracture, accounting for the high rate of work-hardening observed in this steel.

The FN of type 202 increases less rapidly, up to an average value of only 0.7 at fracture. This suggests that the austenite formed in type 202 is considerably more stable with respect to strain-induced α′ martensite formation than the austenite in type 304, and examination of the published percentage martensite with applied strain (Ref 12) (superimposed on Fig. 2) suggests that type 202 is likely to contain less than 5% α′ martensite at fracture.

The formation of strain-induced martensite on deformation appears to have a marginal effect on the high rate of work-hardening observed for type 202. The slightly higher rate of work-hardening observed in Fig. 1 for type 202 can therefore be attributed to a lower SFE, due to the reduced nickel content of this grade.

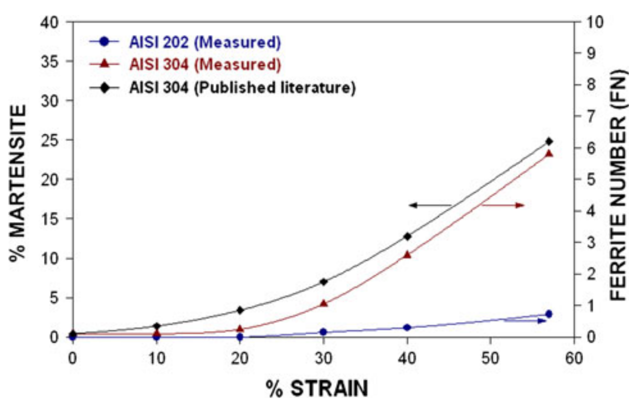

Fig. 2 The measured ferrite number for AISI 304 and AISI 202 as a function of percentage applied strain. Superimposed on the graph is the percentage α′ martensite in AISI 304 as a function of strain (from Ref 12)

3.2 Tensile Tests to Fracture

The results obtained from tensile tests to fracture are shown in Table 2 as the average values acquired in four tests performed for each set of experimental conditions. In this table, YS is the 0.2% proof stress, UTS is the ultimate tensile strength, e_u is the uniform elongation, and e_t is the total elongation at fracture. The term X refers to the property of interest in different directions relative to the rolling direction, and the average values, X_m, were calculated from Eq 1 (Ref 13). Figures 3 and 4 display the measured tensile curves (engineering stress versus engineering strain) for AISI 304 and AISI 202, respectively. The smooth shapes of both tensile curves and the absence of any sharp inflections beyond yield point confirm that the austenite in both alloys is largely stable with respect to the formation of strain-induced martensite (Ref 13).

$$X_m = \frac{X_0 + 2X_{45} + X_{90}}{4} \quad \text{(Eq 1)}$$

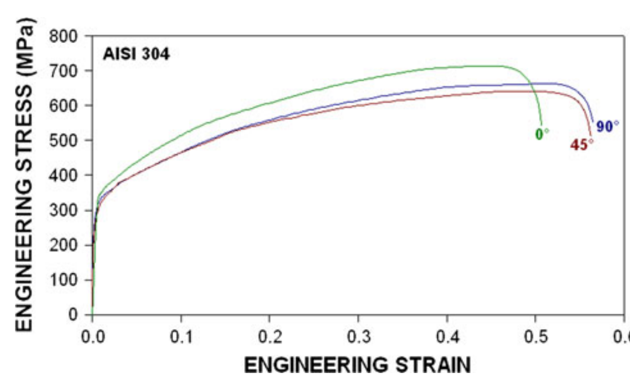

Fig. 3 Measured engineering stress-engineering strain curve for AISI 304

Table 2 Tensile properties of the two materials

Type	Property in different directions	YS, MPa	UTS, MPa	UTS:YS	e_u, %	e_t, %	n	K, MPa
AISI 304	X_0	293	709	2.42	47	54	0.41	1481
	X_{45}	275	640	2.33	50	57	0.42	1370
	X_{90}	292	660	2.26	52	58	0.41	1395
	X_m	284	662	2.33	50	57	0.42	1404
AISI 202	X_0	285	656	2.30	45	53	0.38	1348
	X_{45}	279	620	2.22	51	58	0.39	1279
	X_{90}	287	630	2.20	50	58	0.39	1303
	X_m	283	631	2.23	49	57	0.39	1302

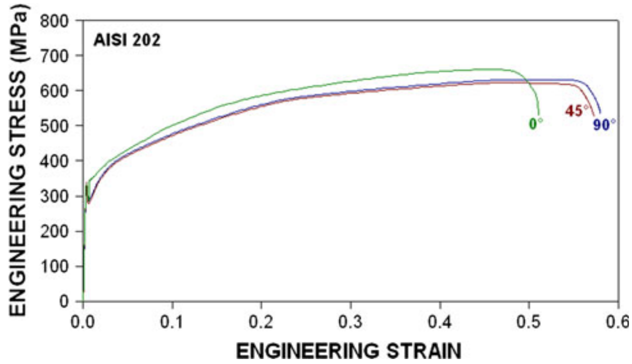

Fig. 4 Measured engineering stress-engineering strain curve for AISI 202

The two grades of stainless steel display very similar tensile properties, with the exception of a slightly higher UTS in AISI 304. The ratio of the ultimate tensile strength to the yield stress (UTS:YS), shown in Table 2, is slightly higher for type 304 than for type 202, and considerably higher that the ratio of 1.8 that is typical for stable austenitic stainless steels (Ref 13). These results suggest that some martensite formation on deformation is expected in both alloys (Ref 13), as confirmed by the FN measurements for AISI 304 (Fig. 2). However, AISI 202 showed very little magnetic response with increasing strain. It is possible that metastable ε martensite (non-magnetic) remained stable over a wider strain range for type 202, but this was not investigated further in this study.

The average values of the strain-hardening exponent, n, and the strength coefficient, K, as defined by the Hollomon relationship (shown in Eq 2), were determined from the region of uniform plastic deformation on the true stress-true strain curves for both alloys. These values are included in Table 2.

$$\sigma = K\varepsilon^n \qquad \text{(Eq 2)}$$

where σ is the true stress, and ε is the true strain.

The strain-hardening exponent, n, of type 202 is approximately 7% higher than that of type 304. This supports the hardness measurements shown in Fig. 1, which indicate that type 202 work-hardens at a higher rate than type 304. In general, high n values lead to good formability in stretching operations, but are reported to have little effect on deep drawability (Ref 14). Both steels show very similar post-uniform elongation values, e_t-e_u, of 7 to 8%.

3.3 Plastic Anisotropic Properties

The R-value, given by Eq 3, is the plastic strain ratio of width to thickness in a sheet, and is a measure of the ability of a material to resist through thickness thinning during drawing. R represents the normal anisotropy, with a high R-value indicating a high resistance to thinning in the thickness direction and good drawing properties (Ref 14). Since most sheet metals show a variation in elastic and plastic properties with orientation relative to the rolling direction, the average normal anisotropy, R_{avg}, can be determined from measurements taken at different angles to the rolling direction. During the course of this investigation, the plastic strain ratios measured at 0°, 45°, and 90° to the rolling direction were utilized to calculate R_{avg} from Eq 4. The plastic strain ratios measured in different orientations relative to the rolling direction, and the calculated average normal anisotropy, R_{avg}, are shown in Table 3 for both alloys.

Table 3 The plastic anisotropic properties of the AISI 304 and AISI 202 stainless steel sheets tested during the course of this investigation

Type	R_0	R_{45}	R_{90}	R_{avg}	ΔR	LDR
AISI 304	2.78	2.65	1.66	2.44	−0.22	2.68
AISI 202	2.81	3.57	2.05	3.00	−0.57	2.75

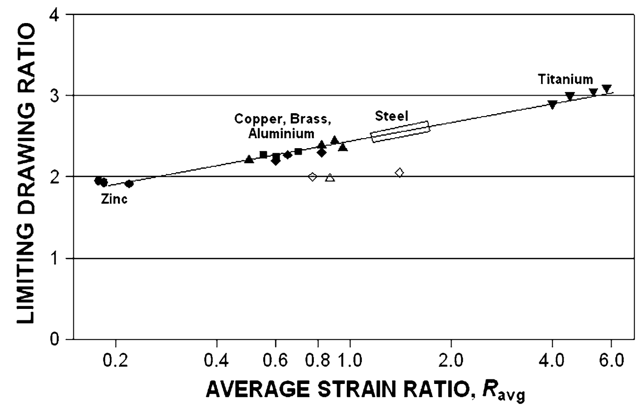

Fig. 5 Correlation between the limiting drawing ratio (LDR) and R_{avg} for a wide range of sheet metals (Ref 14)

$$R = \frac{\ln(w_0/w)}{\ln(h_0/h)} \qquad \text{(Eq 3)}$$

where w_0, w are the initial and final widths of the sheet, and h_0, h are the initial and final thicknesses.

$$R_{avg} = \frac{R_0 + 2R_{45} + R_{90}}{4} \qquad \text{(Eq 4)}$$

where R_0 is the plastic strain ratio at 0° to the rolling direction, R_{45} is the plastic strain ratio at 45° to the rolling direction, and R_{90} is the plastic strain ratio at 90° to the rolling direction.

As shown in Table 3, the average normal anisotropy, R_{avg}, of type 202 is considerably higher than that of type 304 (approximately 23% greater). Although both stainless steels have high R_{avg} values and are therefore expected to display good deep drawing properties, the results suggest that AISI 202 should have a higher resistance to through thickness thinning and therefore possess superior drawing properties compared to type 304.

The R_{avg} values shown in Table 3 can be used to determine the limiting drawing ratio, LDR, for the two stainless steels. For any given material, the LDR gives an indication of the largest blank that can be drawn through a die without tearing (Ref 14). In this study, Atkinson's correlation between the average normal anisotropy, R_{avg}, and the LDR (shown graphically in Fig. 5; Ref 14) was used for determining the LDR of the two grades. The limiting drawing ratios of types 202 and 304 measured during the course of this investigation are shown in Table 3. The LDR for type 304 is higher than the reported range of 2.18 to 2.25 (Ref 13). The high LDR values shown in Table 3 suggest that both steels will exhibit good deep drawing properties.

The material properties of AISI 202 have been shown to vary with orientation relative to the rolling direction. Kumar

Table 4 The average cup heights measured for type 304 and type 202 stainless steel during Erichsen cupping tests

Type	Erichsen cupping height, mm
AISI 304	8.42
AISI 202	8.26

has reported a reduction in the work-hardening exponent when measured transverse to the rolling direction (Ref 15). The planar anisotropy, ΔR, represents the dependence of material properties on orientation relative to the rolling direction. and predicts the extent of earing during deep drawing. Earing is defined as the formation of a wavy edge on top of the drawn cup, which necessitates extensive trimming to produce a uniform top (Ref 14). The planar anisotropy can be calculated from the plastic strain ratios measured in different directions relative to the rolling direction (as shown in Eq 5; Ref 13).

$$\Delta R = \frac{R_0 - 2R_{45} + R_{90}}{2} \quad \text{(Eq 5)}$$

A combination of a high R_{avg} value and a low ΔR value provides optimal deep drawing properties. As shown in Table 3, the ΔR values of both alloys deviate from the optimum of zero, suggesting that earing can be expected in both steels during deep drawing. Type 202 is expected to be more susceptible to earing than type 304.

3.4 Erichsen Cupping Tests

The average cup heights measured for three Erichsen cupping tests for each alloy are shown in Table 4. There is little difference between the cup heights, suggesting that type 304 and type 202 have very similar deep drawing properties.

4. Conclusions

The formability of an austenitic Cr-Mn-N stainless steel, grade AISI 202, was compared with that of type AISI 304 using Erichsen cupping tests and uniaxial tensile tests performed at various angles to the rolling direction. The results of this investigation suggest that the two grades of stainless steel have very similar deep drawing properties.

- The hardness values of both grades of stainless steel increase with strain up to final fracture, but AISI 202 appears to work-harden at a slightly higher rate than AISI 304. FN measurements indicate that the more deformation-induced α' martensite formed in AISI 304, which implies that the higher rate of work-hardening in AISI 202, is mainly due to work-hardening in the austenite itself as a result of dislocation interactions.
- The two grades of stainless steel display very similar tensile properties. The strain hardening exponent of AISI 202 is approximately 7% higher than that of AISI 304, confirming that grade 202 work-hardens at a slightly higher rate during forming.
- The average normal anisotropy (R_{avg}) values and limiting drawing ratios of both grades are high, implying good deep drawing properties. The R_{avg} value of type 202 is approximately 23% higher than that of 304, suggesting that AISI 202 has a higher resistance to through thickness thinning. AISI 202 also displays a higher LDR than AISI 304. Both grades are predicted to be susceptible to earing during deep drawing operations.
- Similar cup heights were measured during Erichsen cupping tests, confirming that the two grades have very similar deep drawing properties.

These results suggest that AISI 202 is a suitable alternative for AISI 304 in applications requiring good deep drawing properties.

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