DOI 10.1007/s11015-017-0531-8
Metallurgist, Vol. 61, Nos. 7–8, November, 2017 (Russian Original Nos. 7–8, July–August, 2017)

QUANTITATIVE EVALUATION OF METALLURGICAL MECHANISMS AFFECTING STRENGTH OF AUSTENITIC STAINLESS STEELS

A. Di Schino

UDC 669.14.018.8:669_122.2:669–153.6

Relations predicting the mechanical properties of bars of austenitic stainless steels are already available, but no systematic work has been performed to predict the strength of cold rolled and annealed stainless steels. The tensile properties of a large number of cold rolled and annealed AISI 304 stainless steel are here correlated with their chemical composition and microstructure. Quantitative effects of various strengthening mechanisms such as grain size, δ-ferrite content and solid solution strengthening by both interstitial and substitutional solutes are described. Interstitial solutes have by far the greatest strengthening effect and, among the substitutional solutes, the ferrite-stabilizing elements have a greater effect than the austenite-stabilizing elements. Regression equations are developed that predict with good accuracy the proof stress and tensile strength in AISI 304 stainless steels.

Keywords: *stainless steels, austenitic, mechanical properties, grain size, ferrite.*

1. Introduction. It is well known that the mechanical properties of austenitic stainless steels are strongly affected by microstructural features (such as grain size and the δ-ferrite content) and chemical composition variations (which produce solid-solution hardening by both substitutional and interstitial solid solution). However, no systematic work to quantify the effect of these variables on cold rolled and annealed stainless steels has been reported other than the pioneering works by Pickering et al. [1, 2], who predicted the mechanical properties of bars of austenitic stainless steels. Moreover, there have been recently commercial developments to exploit the effect of these variables both from the point of view of grain size [3] and by composition variations [4, 5] in order to improve the mechanical properties of the steel. Furthermore, the stainless steel production route has been vastly improved in the last years by the use of argon oxygen decarburization (AOD) so that the stainless steels examined by Pickering and colleagues are quite different from the actual ones. Consequently, a systematic investigation has been carried out to obtain a quantitative relationship between microstructure, composition, and mechanical properties of AISI 304 stainless steel.

In view of the successful application of the statistical techniques to the relationship between mechanical properties and microstructure of C–Mn steels with ferrite-perlite structures [6] and of austenitic stainless steels in the state of bars [1], a similar approach has been here adopted for cold rolled and annealed AISI 304 steel.

2. Experimental. In order to examine the effect of the different alloying elements, a series of 100 industrially produced AISI 304 stainless steels was examined. The main composition of the steels is given in Table 1. The materials were subjected to cold rolling down to about 1 mm thickness, to subsequent annealing at 1100°C and pickling on the industrial line. They were then water quenched in order to minimize any precipitation effects during cooling.

Transverse tensile specimens were prepared from the cold rolled and annealed steels according to the ISO 80 norm. Tensile tests have been performed with a Zwick traction machine. The speed in the elastic region was 2 mm/min, and that in

Università di Perugia, Perugia, Italy; e-mail: andrea.dischino@unipg.it. Published (Russian translation) in Metallurg, No. 7, pp. 42–46, July, 2017. Original article submitted October 10, 2016.

TABLE 1. Main Composition of the Considered Steels

Steel No.	C, %	N, %	Si, %	Mn, %	Cr, %	Ni, %	Cu, %
1	0.041	0.049	0.41	1.51	18.07	8.58	0.19
2	0.024	0.048	0.47	1.09	18.17	10.09	0.24
3	0.042	0.053	0.39	1.50	18.12	8.51	0.23
4	0.038	0.031	0.36	1.53	18.09	9.02	0.21
5	0.040	0.024	0.36	1.54	18.39	9.01	0.32
6	0.038	0.020	0.40	1.51	18.06	9.05	0.18
7	0.043	0.024	0.43	1.50	18.00	9.06	0.17
8	0.038	0.017	0.49	1.50	18.06	9.04	0.09
9	0.037	0.045	0.42	1.58	18.33	8.56	0.31
10	0.048	0.024	0.35	1.53	18.10	9.04	0.23
11	0.035	0.031	0.37	1.58	18.08	9.07	0.28
12	0.036	0.045	0.34	1.51	18.11	8.58	0.26
13	0.055	0.027	0.37	1.54	18.16	8.88	0.26
14	0.041	0.026	0.40	1.54	18.06	9.02	0.19
15	0.038	0.028	0.34	1.54	18.05	9.05	0.30
16	0.041	0.024	0.35	1.50	18.25	9.05	0.26
17	0.042	0.021	0.34	1.53	18.07	9.00	0.23
18	0.045	0.041	0.43	1.60	18.05	8.51	0.29
19	0.042	0.033	0.37	1.57	18.26	9.01	0.21
20	0.042	0.030	0.33	1.51	18.20	9.13	0.28
21	0.038	0.031	0.36	1.53	18.09	9.02	0.21
22	0.040	0.044	0.37	1.53	18.05	8.55	0.09
23	0.017	0.041	0.35	1.57	18.05	8.83	0.27
24	0.043	0.032	0.38	1.52	18.12	9.03	0.27
25	0.018	0.044	0.00	1.55	18.05	8.80	0.33
26	0.023	0.042	0.00	1.57	18.44	8.85	0.24
27	0.043	0.048	0.00	1.32	18.09	8.50	0.23
28	0.043	0.046	0.00	1.33	18.11	8.52	0.26
29	0.038	0.024	0.00	1.34	18.09	9.03	0.26
30	0.022	0.035	0.00	1.58	18.13	8.82	0.23
31	0.050	0.047	0.33	1.44	18.19	8.55	0.23
32	0.005	0.044	0.39	1.32	18.31	8.50	0.28
33	0.005	0.042	0.38	1.30	18.11	8.51	0.30
34	0.051	0.049	0.31	1.33	18.06	8.50	0.18
35	0.044	0.051	0.37	1.34	18.29	8.60	0.26
36	0.051	0.052	0.33	1.31	18.05	8.53	0.30
37	0.038	0.042	0.33	1.33	18.06	8.50	0.21
38	0.044	0.037	0.31	1.32	18.09	8.52	0.24
39	0.050	0.042	0.42	1.33	18.05	8.51	0.25
40	0.047	0.042	0.38	1.31	18.08	8.52	0.20
41	0.041	0.047	0.38	1.40	18.24	8.52	0.21

TABLE 1. Continued

Steel No.	C, %	N, %	Si, %	Mn, %	Cr, %	Ni, %	Cu, %
42	0.043	0.049	0.37	1.34	18.16	8.50	0.20
43	0.045	0.046	0.31	1.35	18.05	8.51	0.26
44	0.040	0.046	0.30	1.37	18.46	8.52	0.26
45	0.045	0.046	0.35	1.41	18.30	8.50	0.23
46	0.041	0.043	0.35	1.35	18.05	8.58	0.20
47	0.034	0.051	0.39	1.31	18.07	8.52	0.20
48	0.035	0.049	0.37	1.30	18.13	8.55	0.25
49	0.043	0.053	0.37	1.31	18.06	8.51	0.26
50	0.043	0.045	0.51	1.31	18.04	8.57	0.26
51	0.045	0.048	0.34	1.33	18.10	8.51	0.27
52	0.048	0.045	0.32	1.31	18.09	8.51	0.25
53	0.047	0.045	0.36	1.33	18.10	8.50	0.25
54	0.039	0.042	0.35	1.31	18.01	8.59	0.28
55	0.042	0.046	0.42	1.39	18.06	8.50	0.28
56	0.047	0.042	0.32	1.36	18.15	8.53	0.28
57	0.045	0.043	0.32	1.38	18.21	8.50	0.24
58	0.021	0.040	0.57	1.08	18.22	10.00	0.26
59	0.020	0.045	0.52	1.19	18.48	10.01	0.27
60	0.016	0.039	0.50	1.19	18.33	10.02	0.26
61	0.030	0.049	0.55	1.02	18.01	10.04	0.23
62	0.025	0.044	0.61	1.14	18.13	10.05	0.23
63	0.015	0.039	0.34	1.33	18.71	9.05	0.24
64	0.027	0.041	0.38	1.35	18.09	9.11	0.26
65	0.026	0.038	0.35	1.32	18.06	9.04	0.26
66	0.033	0.046	0.30	1.31	18.06	9.01	0.25
67	0.031	0.039	0.33	1.31	18.07	9.02	0.25
68	0.023	0.039	0.32	1.31	18.04	9.05	0.25
69	0.026	0.045	0.32	1.34	18.16	9.04	0.25
70	0.022	0.042	0.31	1.37	18.24	9.02	0.25
71	0.027	0.037	0.32	1.39	18.14	9.05	0.25
72	0.027	0.035	0.35	1.39	18.15	9.06	0.30
73	0.025	0.048	0.32	1.36	18.18	9.06	0.30
74	0.030	0.041	0.34	1.32	18.10	9.05	0.28
75	0.029	0.039	0.30	1.33	18.07	9.00	0.25
76	0.024	0.035	0.37	1.32	18.12	9.06	0.26
77	0.021	0.042	0.37	1.34	18.13	9.00	0.23
78	0.029	0.038	0.36	1.33	18.31	9.00	0.25
79	0.022	0.047	0.32	1.33	18.48	9.04	0.20
80	0.028	0.040	0.33	1.33	18.23	9.02	0.25
81	0.027	0.036	0.35	1.32	18.07	9.00	0.30
82	0.027	0.041	0.32	1.32	18.10	9.02	0.23

TABLE 1. Continued

Steel No.	C, %	N, %	Si, %	Mn, %	Cr, %	Ni, %	Cu, %
83	0.029	0.046	0.30	1.32	18.22	9.01	0.30
84	0.019	0.038	0.33	1.30	18.46	9.03	0.28
85	0.033	0.040	0.32	1.35	18.33	9.00	0.21
86	0.024	0.046	0.35	1.38	18.31	9.00	0.21
87	0.023	0.044	0.34	1.38	18.11	9.01	0.22
88	0.044	0.043	0.35	1.44	18.16	8.51	0.23
89	0.041	0.043	0.35	1.35	18.05	8.58	0.28
90	0.043	0.046	0.32	1.33	18.11	8.52	0.28
91	0.050	0.046	0.35	1.34	18.01	8.51	0.22
92	0.055	0.048	0.31	1.39	18.27	8.82	0.12
93	0.020	0.047	0.31	1.34	18.05	8.52	0.23
94	0.042	0.050	0.30	1.32	18.12	8.52	0.24
95	0.016	0.046	0.05	1.05	18.11	10.12	0.15
96	0.021	0.042	0.56	1.12	18.19	10.00	0.25
97	0.053	0.048	0.34	1.36	18.19	8.57	0.29
98	0.038	0.039	0.34	1.36	18.32	8.54	0.22
99	0.051	0.040	0.36	1.33	18.04	8.51	0.27
100	0.048	0.041	0.40	1.32	18.23	8.50	0.26

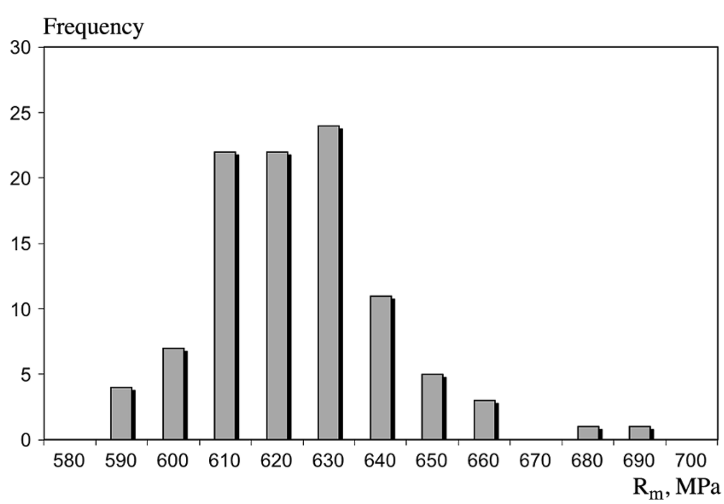

Fig. 1. R_m of the examined AISI 304 steels.

the plastic region 20 mm/min. Measurements were carried out of the 0.2% proof stress (R_{p02}), tensile strength (R_m), and elongation (A). An Ermco automatic instrument was used for hardness measurements (HRB).

Transverse sections were prepared from the undeformed region of each tensile specimen and were etched with a solution containing HNO_3 + HCl to reveal the austenite grains. Etching with a solution containing NaOH was used to highlight any δ-ferrite present.

Metallographic measurements were carried out through an automatic image analyzer to determine the austenite grain size (*d*) and the volume fraction of δ-ferrite.

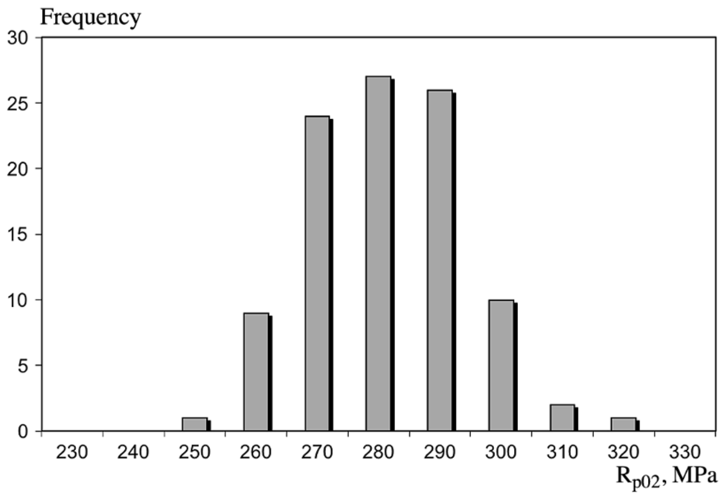

Fig. 2. R_{p02} of the examined AISI 304 steels.

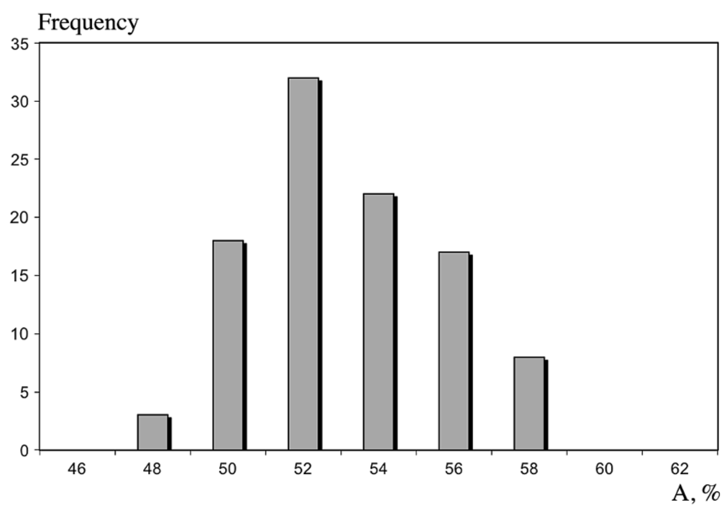

Fig. 3. Elongation A of the examined AISI 304 steels.

3. Results and discussion. The distributions of the mechanical properties of the examined steels, as obtained by tensile test and by hardness measurements, are shown in Figs. 1–4, which show that the 0.2% yield stress ranges from 250 to 320 MPa and that the tensile strength ranges from 590 to 690 MPa. Due to these considerable variations in the mechanical properties of AISI 304, there is the need to correlate these properties with the chemical composition, the grain dimension, and the δ-ferrite content. For this purpose, the basic statistical technique employed was the multiple regression analysis.

The metallurgical aspects considered for the regression analysis are discussed in the following.

Grain size. Because of the well-known relationship between the mechanical properties and the reciprocal of the square root of the grain diameter d [7], a relationship between the generic mechanical property σ_i and $d^{-1/2}$ was used.

δ-Ferrite content. Previous experiences [1] with the effect of a second phase on austenitic stainless steels have shown that the flow stress and the tensile strength at any given strain are linearly related to the volume fraction of the second phase. Consequently, the volume fraction of the δ-ferrite was used directly in the regression analysis.

Solid-solution effects. There are some doubts concerning the exact functional relationship between the mechanical properties and the concentration of the solutes. It was considered, however, that, because the concentration of any particular

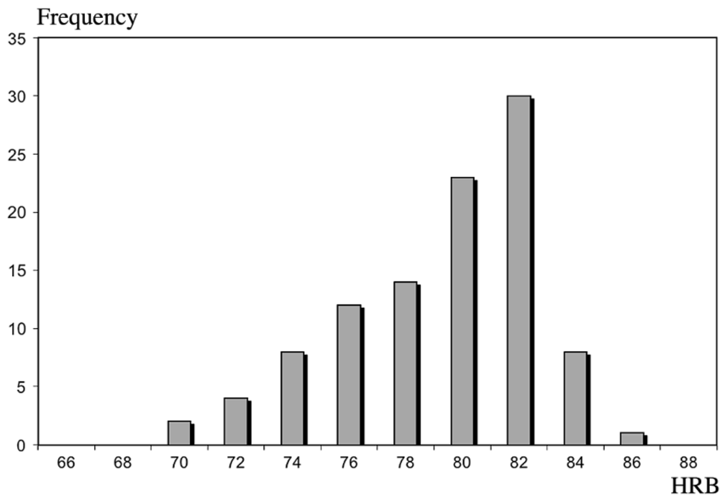

Fig. 4. HRB of the examined AISI 304 steels.

element varied over a restricted range, the precise function could be satisfactorily approximated by a linear relationship for the solute concentration, in agreement with Pickering et al. [1]. Then, concerning the prediction of the of the tensile stress (R_m) and of the 0.2% yield stress (R_{p02}) the validity of the following classical relationship [1] has been tested:

$$R_m \text{ (MPa)} = 15.4[29 + 35(\%C) + 55(\%N) + 2.4(\%Si) + 0.11(\%Ni) + 1.2(\%Mo) + 5.0(Nb) + \\ + 0.14(\%\delta\text{-ferrite} + 0.82d^{-1/2}]; \quad (1)$$

$$R_{p02} \text{ (MPa)} = 15.4[4.4 + 23(\%C) + 1.3(\%Si) + 0.24(\%Cr) + 0.94(\%Mo) + \\ + 2.6(\%Nb) + 32(\%N) + 0.16(\%\delta\text{-ferrite}) + 0.46d^{-1/2}]. \quad (2)$$

In Fig. 5, the experimental tensile strength is plotted versus the tensile strength calculated according to Eq. (1). The points should lie on the dashed line in the case of a successful prediction. This figure shows that the Pickering relation can be used to predict the tensile strength in AISI 304 stainless steel with good accuracy. To analyze the applicability of Eq. (1) over the whole range of variation of the chemical composition of AISI 304 steel, the ratio R_m^{exp}/R_m^{th} is plotted in Fig. 6 versus the ratio Cr_{eq}/Ni_{eq} calculated according to the classical relationships by Hammar and Svensson [8]:

$$Cr_{eq} = (\%Cr) + 1.37(\%Mo) + 1.5(\%Si) + 2.0(\%Nb) + 3.0(\%Ti); \quad (3)$$

$$Ni_{eq} = (\%Ni) + 22.0(\%C) + 14.2(\%N) + 0.31(\%Mn) + (\%Cu). \quad (4)$$

Also in this plot the points should lie on the dashed line in the case of a successful prediction. Then it can be concluded that Eq. (1) is able to predict the tensile strength over the range of variation of the equivalent ratio Cr_{eq}/Ni_{eq} of AISI 304 steel with an accuracy of 5%.

Figure 7 shows that the values of the 0.2% yield stress calculated according to the Pickering relation (Eq. (2)) are all lower than the experimental ones. This means that the Pickering relations, originally developed to predict the mechanical properties in hot rolled sheets of austenitic stainless steels, in the case of cold rolled and annealed steels can be applied to predict the value of the tensile strength but not that of 0.2% yield stress. One of the possible reasons for this lack of validity can lie in the different ferrite contents of the hot rolled sheets with respect to the cold rolled steels and hence to the use of the Pickering relations in a different range of ferrite concentration than the original one. In fact it is well known that the 0.2% yield stress is much more affected by the presence of second phase particles with respect to the tensile stress [2].

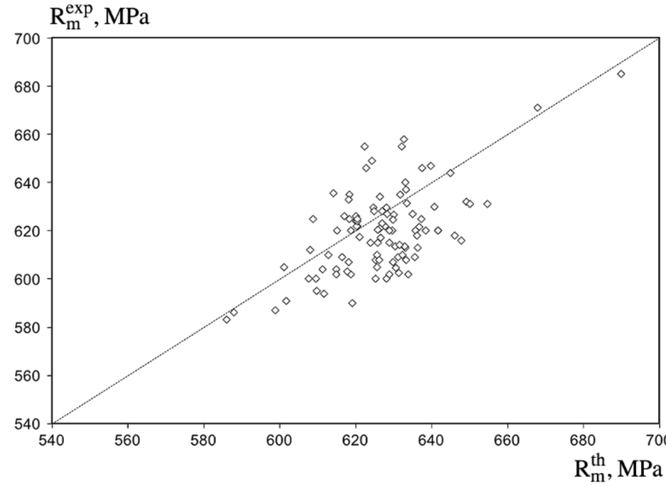

Fig. 5. Prediction of the tensile stress according to (1). Multiple-R^2 = 0.95.

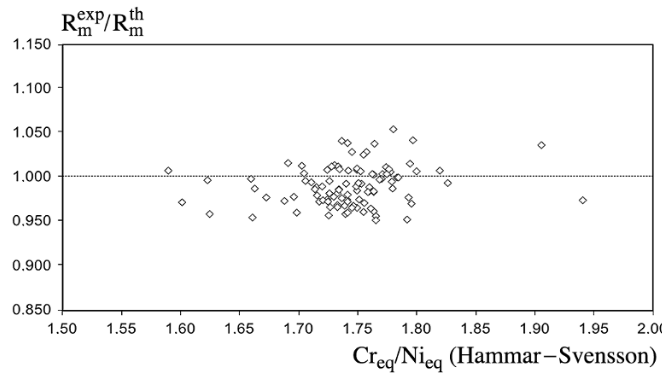

Fig. 6. R_m^{exp}/R_m^{th} versus Cr_{eq}/Ni_{eq} calculated according to the classical relationships by Hammar and Svensson [8].

A new relation has been then assessed to predict the value of the 0.2% yield stress. Because of the difficulty to perform a multi-linear regression depending on all the parameters, due to the small variation of some elements, just the interstitial element C and N and the δ-ferrite content were considered as free parameters. For all the other chemical elements and for the grain size contribution, the coefficients were chosen according to Eq. (2). Then, the following regression has been performed, with a multiple R^2 = 0.972:

$$R_{p02}\ (\text{MPa}) = 15.4[4.4 + 27.18(\%\text{C}) + 1.3(\%\text{Si}) + 0.24(\%\text{Cr}) +$$

$$+ 0.94\text{Mo} + 2.6(\%\text{Nb}) + 56.85\text{N} + 16.34(\%\delta\text{-ferrite}) + 0.46d^{-1/2}]. \quad (5)$$

Interstitial solutes have by far the greatest strengthening effect. Although the δ-ferrite content is lower than in the materials studied by Pickering, its effects are enhanced with respect to Eq. (2). This effect has been also reported for the 0.2% yield stress in carbon steels [9]. The representation of the 0.2% yield stress, computed according to Eq. (5), is shown in Fig. 8. Now, the experimental points lie on the dashed line, indicating a much better prediction with respect to Eq. (2) and Fig. 7 results.

Furthermore, the elongation A and the hardness HRB are shown as a function of R_{p02} in Figs. 9 and 10, respectively. In both cases, a smooth linear dependence is evident.

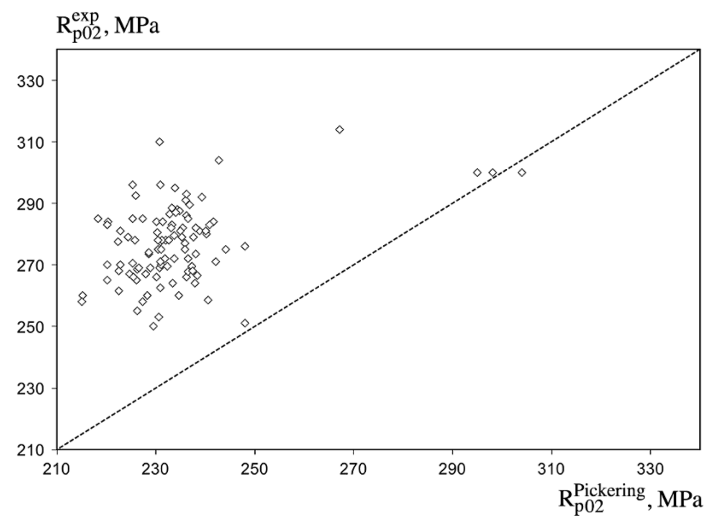

Fig. 7. Experimental R_{p02} versus R_{p02} calculated according to relationship (2).

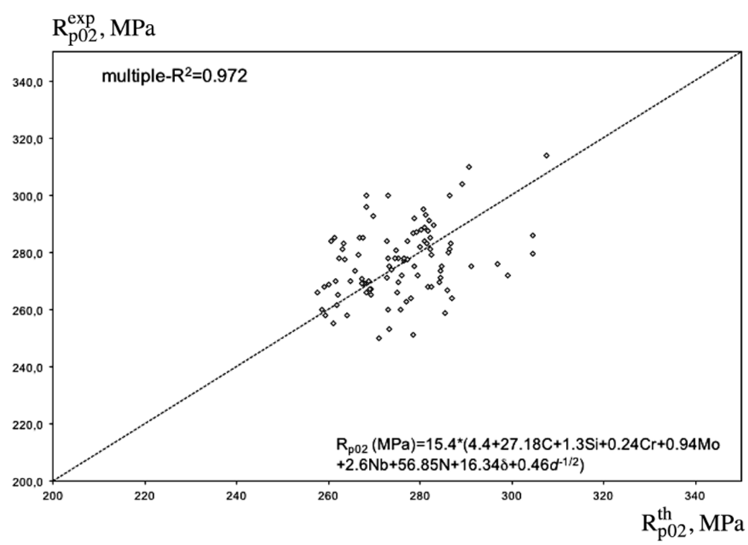

Fig. 8. Prediction of the 0.2% proof stress according to (3). Multiple-R^2 = 0.97.

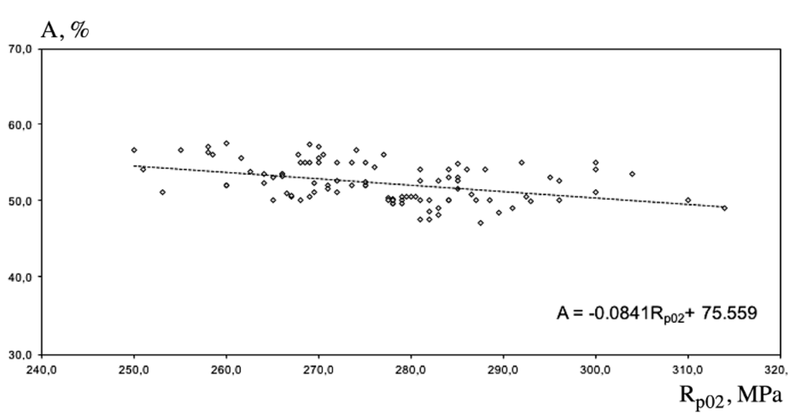

Fig. 9. Elongation A versus 0.2% proof stress. R^2 = 0.88.

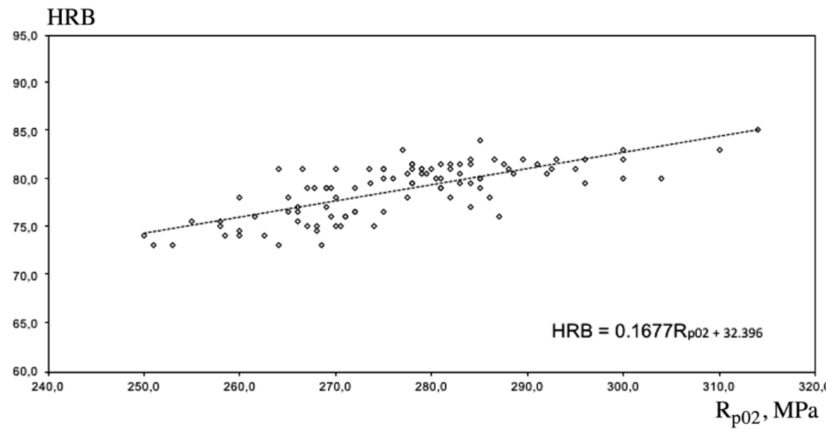

Fig. 10. Hardness HRB versus 0.2% proof stress. $R^2 = 0.87$.

From the results obtained, it is possible to conclude that the mechanical properties of the cold rolled and annealed steels studied can be predicted by multi-linear regression once the chemical composition and the microstructural features of the steel are known.

4. Conclusions.

The tensile properties of a large number of cold rolled and annealed AISI 304 stainless steels have been correlated with their chemical composition and microstructure. Quantitative effects of various strengthening mechanisms such as grain size, δ-ferrite content, and solid solution strengthening by both interstitial and substitutional solutes have been described, and regression equations able to predict the yield stress and tensile strength of AISI 304 stainless steels have been developed. It has also been demonstrated that interstitial solutes have by far the greatest strengthening effect and, among the substitutional solutes, the ferrite-stabilizing elements have a greater effect than the austenite-stabilizing elements.

REFERENCES

1. K. J. Irvine, T. Gladman, and F. B. Pickering, *J. Iron Steel Inst.*, **207**, 1017 (1969).
2. F. B. Pickering, *Int. Met. Rev.*, 227 (1976).
3. Y. Murata, T. Takemoto, and Y. Uematsu., in: *Proc. Int. Conf. on Stainless Steels*, ISIJ, Chiba (1991), p. 510.
4. A. Di Schino, J. M. Kenny, M. G. Mecozzi, and M. Barteri, in: *Proc. 20th Sampe Europe Int. Conf.*, M. Erath (ed.), SAMPE, Paris (1999), p.175.
5. A. Di Schino, M. G. Mecozzi, M. Barteri, and J. M. Kenny, *J. Mater. Sci.*, **35**, 4803 (2000).
6. F. B. Pickering and T. Gladman, *ISI Spec. Rep. 10* (1963).
7. J. N. Petch, *J. Iron Steel Inst.*, **174** (1953).
8. O. Hammar and U. Svensson, in: *Proc. Solidification and Casting of Metals Conf.*, The Metal Society, London (1979), p. 401.
9. R. E. Reed-Hill, *Physical Metallurgy Principles*, D. Van Nostrand Company, London (1964).