EVALUATION OF THE METALLURGICAL PARAMETERS EFFECT ON TENSILE PROPERTIES IN AUSTENITIC STAINLESS STEELS

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Abstract
Even if relations predicting the mechanical properties on bars of austenitic stainless steels are already available, but no systematic works was carried out in order to predict mechanical properties in after cold rolling and annealing. 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 – stabilising elements have a greater effect than the austenite – stabilising elements. Regression equations are developed which predict with good accuracy the proof stress and tensile strength in AISI 304 stainless steels.

Keywords: Stainless steels; mechanical properties

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 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 pionieristic works by Pickering et al. [1-2], who predicted the mechanical properties of bars of austenitic stainless steels. Moreover, there have been commercial developments to exploit the effect of these variables both from the point of view of grain size [3-6] and by composition variations [7-13] in order to improve also fatigue [14-15] and tribological properties of the steel [16]. Furthermore, the stainless steel production route has been heavily improved in the last years by the use of AOD (Argon Oxygen Decarburisation) 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 and is reported in this paper to obtain a quantitative relationship between microstructure, composition and mechanical properties of the 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 [17] and

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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 Materials and experimental details

In order to examine the effect of the different alloying elements, a series of one hundred industrially produced AISI 304 stainless steels was examined. The main steel compositions of are 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 industrial line. They were then water quenched in order to minimise 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 the plastic region 20 mm/min. Measurements were carried out of the 0.2% proof stress (R_{p02}), tensile strength (R_m), 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 HNO3+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 automatic image analyser to determine the austenite grain size (d) and the volume fraction of δ-ferrite.

3 Results

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 MPa to 320 MPa and that the tensile strength ranges from 590 MPa to 690 MPa. Due to these considerable variations in the mechanical properties of the 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.

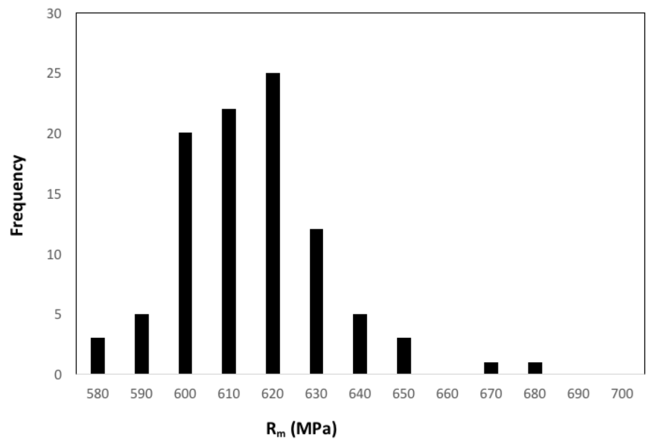

Fig. 1 R_m of the examined AISI 304 steels

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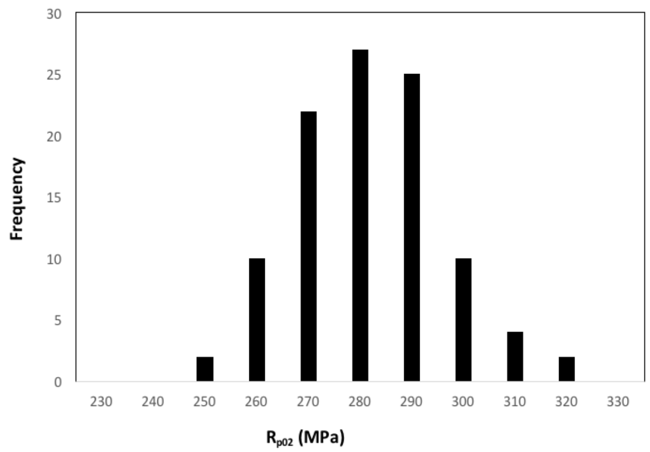

Fig. 2 R_{p02} of the examined AISI 304 steels.

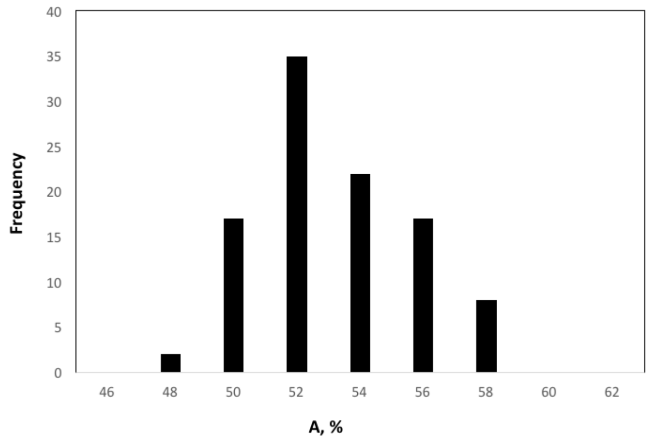

Fig. 3 A% of the examined AISI 304 steels

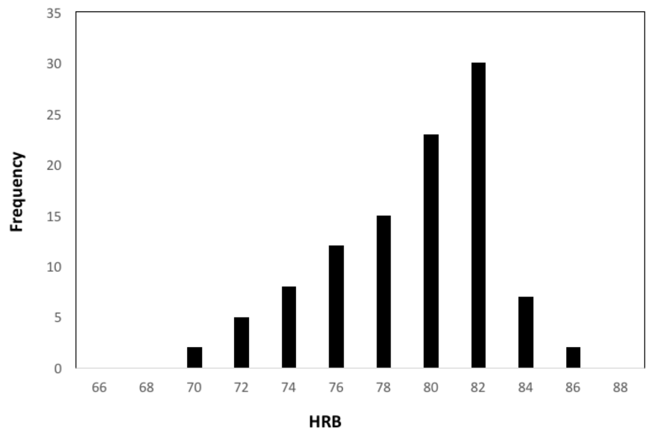

Fig. 4 HRB of the examined AISI 304 steels

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Grain size

Because of the well-known relationship between the mechanical properties and the reciprocal of the square root of the grain diameter d [**18**] a relationship between a generic mechanical property σ_i and $d^{-1/2}$ was used.

δ-ferrite content

Previous experiences [**1**] of the effect of the 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 element varied over a restricted range, the precise function could be satisfactorily approximated by a linear relationship between the solute concentration, in agreement with Pickering et al. [**1**]. Then, concerning the prediction 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:

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

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

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 case of a successful prediction.

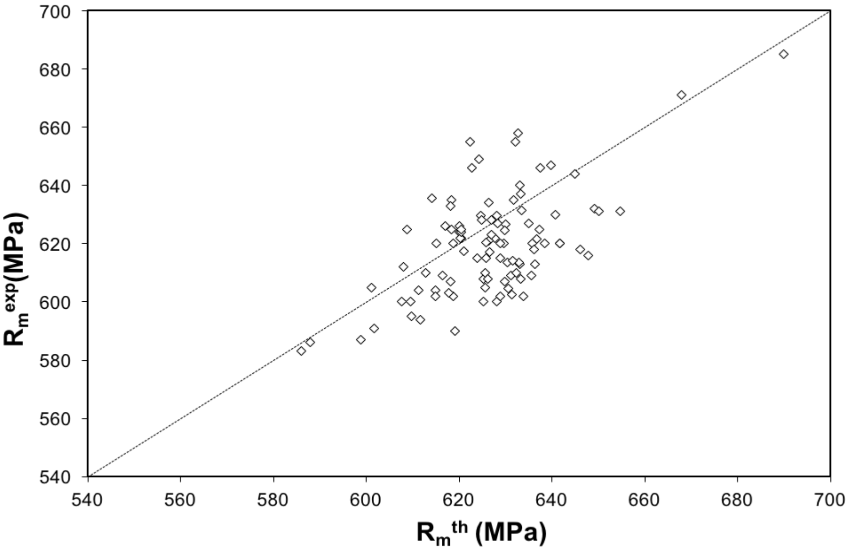

Fig. 5 Prediction of the tensile stress according to (1). Multiple-R2=0.95

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This figure shows that the Pickering relation can be used to predict the tensile strength in AISI 304 stainless steel with good accuracy. To analyse the applicability of Eq. 1 over the whole range of variation of the chemical composition of the AISI 304 steel, the ratio Rm_{exp}/Rm_{th} is plotted in **Fig. 6** versus the ratio Cr_{eq}/Ni_{eq} calculated according to the classical relationships by Hammar and Svensson [**19**]:

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

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

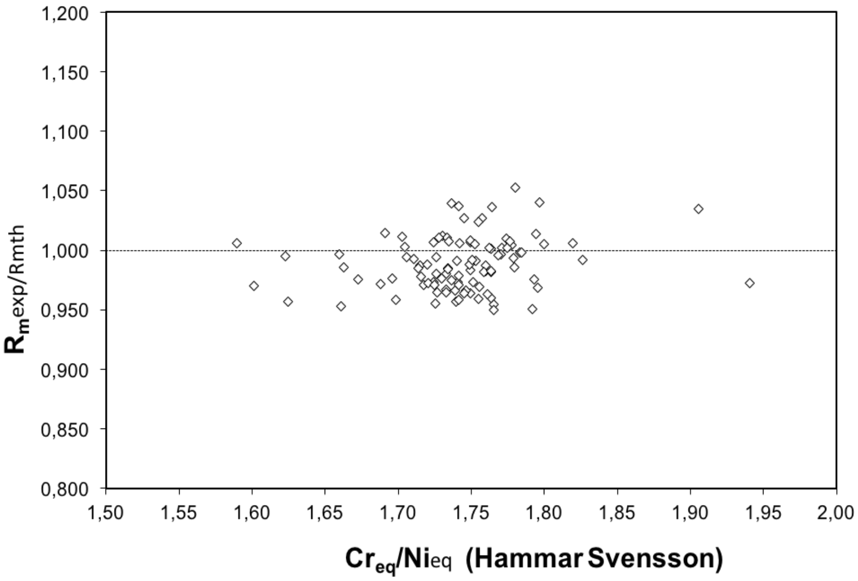

Fig. 6 R_m^{exp}/R_m^{th} versus Cr_{eq}/Ni_{eq} calculated according to the classical relationships by Hammar and Svensson [**19**]

Also in this plot, the points should lie on the dashed line in 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 the AISI 304 steel with an accuracy of 5%.

Fig.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 of 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**].

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 little variation of some elements, just the interstitial element C and N and the δ-ferrite content

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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.

$$R_{p02}(MPa)=15.4[4.4+27.18(\%C)+1.3(\%Si)+0.24(\%Cr)+0.94Mo+2.6(\%Nb)+56.85N+16.34(\%\delta\text{-ferrite})+0.46d^{-1/2}] \quad (5.)$$

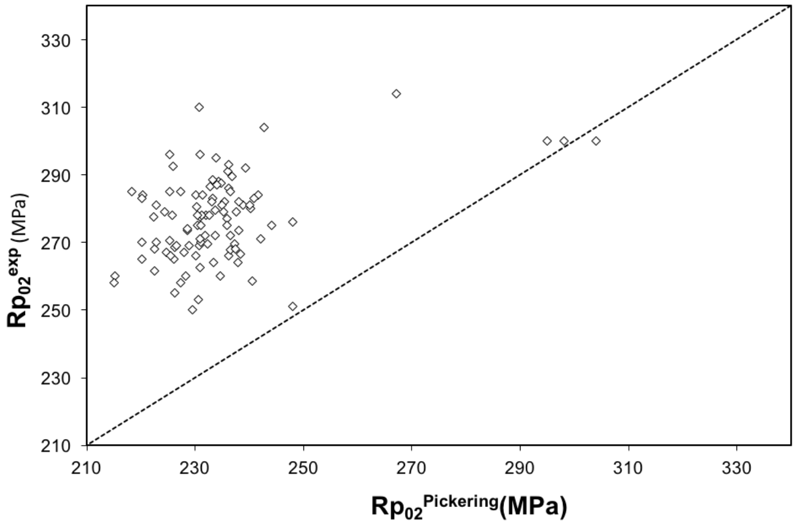

Fig. 7 Experimental R_{p02} versus R_{p02} calculated according to the relationship (2)

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 [**20**]. The representation the 0.2% yield stress, computed according to Eq. 5, is shown in **Fig.8**.

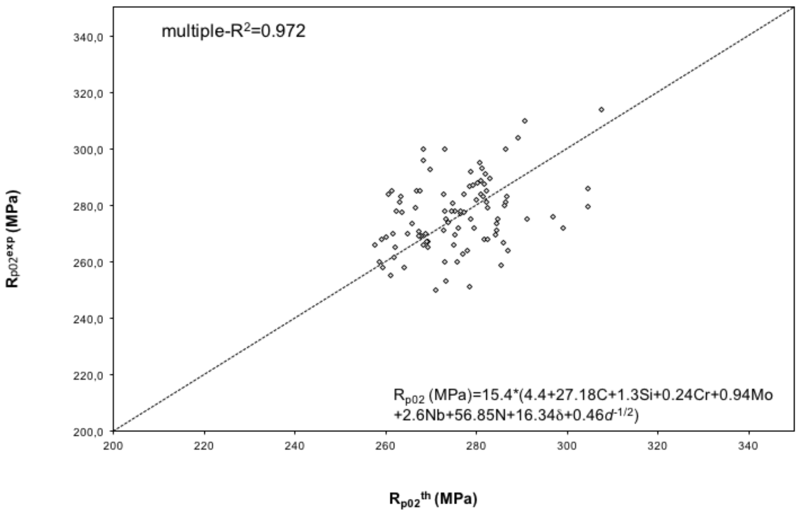

Fig. 8 Prediction of the 0.2% proof stress according to (3). Multiple-R^2=0.97

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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 **Fig.9** and **Fig.10** respectively.

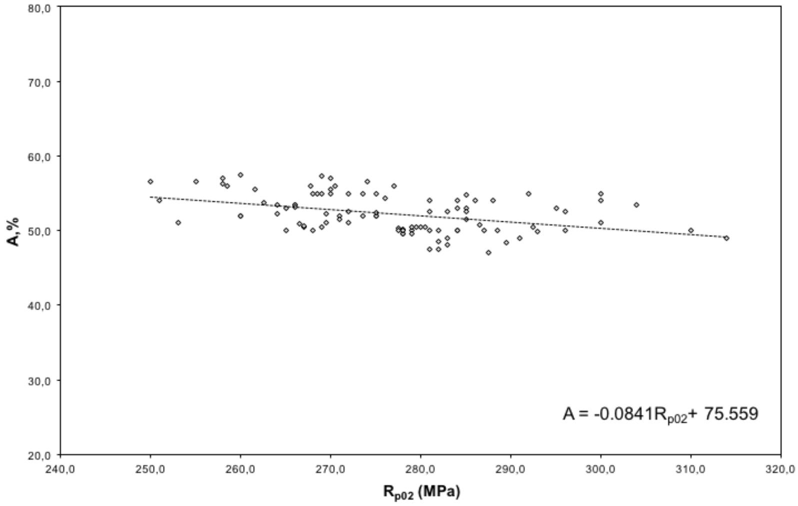

Fig. 9 Elongation A versus 0.2% proof stress. R^2=0.88

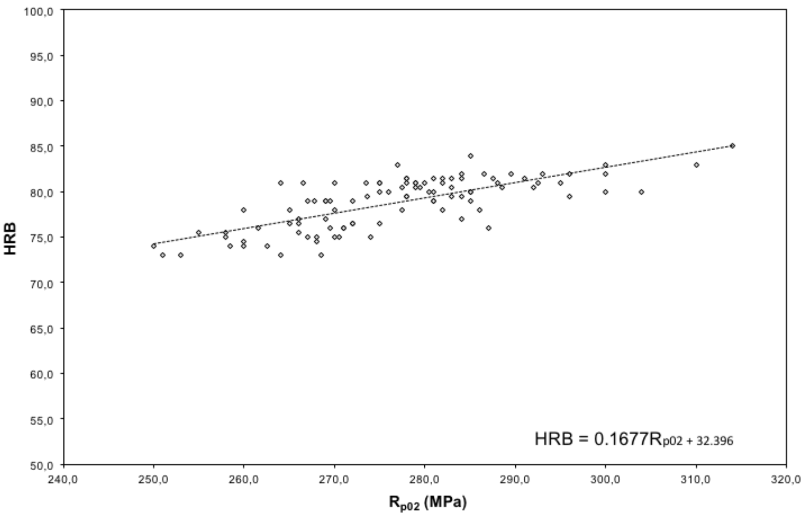

Fig. 10 Hardness HRB versus 0.2% proof stress. R^2=0.87

In both cases a smooth linear dependence is evident. 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.

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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 been also demonstrated that interstitial solutes have by far the greatest strengthening effect and, among the substitutional solutes, the ferrite – stabilising elements have a greater effect than the austenite – stabilising elements.

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Appendix:

Table 1 Main composition of the considered steels

Steel n°	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
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

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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
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

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