VARIANCE OF SELECTED PROPERTIES FROM VARIOUS STRUCTURAL ELEMENTS MADE FROM AISI 304

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Abstract *Stainless steels, especially AISI 304 are widely used civil engineering materials because of their excellent properties. They are used/applied in many civil engineering structures (chemical, energy, bridges etc.). The presented study aims to quantify variance of selected properties from various structural elements made from AISI 304. This study shows that the mechanical and fatigue properties of AISI 304 steel used in construction and supplied in different profiles from different suppliers can vary considerably, which must be taken into account when designing structures or its service-life.*

Keywords

Stainless steel, AISI 304, structural elements, tensile test, S-N curve, fatigue.

1. Introduction

The use of stainless steel for civil engineering structures is relatively recent, 20 to 25 years. In addition to the traditional use as architectural features, guardrails and handrails, stainless steels, especially AISI 304, are increasingly being used for structural components of decks or in suspension systems, as well as in anchorage components. Significant advances in the use of stainless steel in construction are described, for example, in [1-4].

Although stainless steel has no clearly defined yield point [5-7] and has significant strain hardening, the design provisions are based primarily on the perfect elastic–plastic material assumptions similar to carbon steel [8-10].

The purpose of this work is to quantify variance of selected mechanical and fatigue properties from various structural elements made from AISI 304, see Fig. 1 - where is photo of angle bar of dimension 100 × 100 × 10 mm, round bar diameter of 10 mm, flat bars with cross section dimension of 10 × 55 mm, 20 × 60 mm and square cross section bar of 60 × 60 mm.

Some selected properties of AISI 304 were already published focusing on special mechanical measurement e.g. various thickness of specimen [5], improvement of properties by using high density electropulsing [6], effect of low frequency [7] etc.

Mechanical properties are important for practical applications (input data) in civil engineering structural probabilistic analysis, see e.g. [11-13].

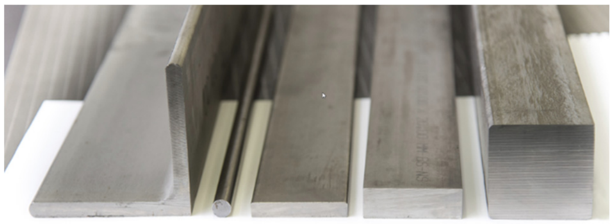


Fig. 1: Different shapes of structural elements made from AISI 304 stainless steel in the shape of angle bar of dimension 100×100×10 mm (marked as L), round bar diameter of 10 mm (marked as D), flat bars with cross section dimension of 10 × 55 mm (marked as PL-10), of 20 × 60 mm (marked as PL-20) and square cross section bar of 60×60 mm (marked as S)

2. Material AISI 304

The AISI 304 steel in the shape of angle bar of dimension 100×100×10 mm (marked as L), round bar with diameter of 10 mm (marked as D), flat bars with cross section dimension of 10 × 55 mm (marked as PL-10), of 20 × 60 mm (marked as PL-20) and square cross section bar with dimension of 60×60 mm (marked as S) was selected for investigation, see Fig.1.

The chemical composition of the investigated steel grades fulfills the EN 10025-2:2004 standard. The composition according to the material lists of the investigated materials is given in Tab. 1. Heat treatment for all studied bars was annealing at 1050°C followed by water quenching. Mechanical properties guaranteed by producers are presented in Tab. 2. Specimen's location for tensile test was selected through cross section to catch the change of materials properties trough and axes of specimen was selected in direction of the supposed crack initiation to be perpendicularly to rolling direction.

Tab. 1: Chemical compositions of AISI 304 for given structural elements (L, D, PL-10, PL-20 and S) according to material lists.

AISI 304	**L**	**D**	**PL-10**	**PL-20**	**S**
C (%)	0.022	0.017	0.019	0.019	0.022
Si (%)	0.37	0.25	0.31	0.31	0.38
Mn (%)	1.58	1.60	1.69	1.69	1.54
P (%)	0.035	0.037	0.035	0.035	0.036
S (%)	0.026	0.024	0.024	0.024	0.026
Cr (%)	18.02	18.2	18.31	18.31	18.34
Ni (%)	8.04	8.10	8.05	8.05	8.04
Mo (%)	0.3	0.43	0.49	0.49	0.36
Ti (%)	0.001	-	0.003	0.003	-
Cu (%)	0.5	0.61	0.47	0.47	0.49
Co (%)	0.17	0.18	0.196	0.196	0.20
N (%)	0.085	0.079	0.090	0.090	0.07
Al (%)	-	-	0.006	0.006	-

Tab. 2: Declared mechanical properties of AISI 304 structural elements (L, D, PL-10, PL-20 and S) by producers at 25°C.

AISI 304	**L**	**D**	**PL-10**	**PL-20**	**S**
R_m [MPa]	637	748	601	601	605
$R_p = 0.2$ % [MPa]	312	633	285	285	311
Elongation [%]	47	69	51	51	49
HBW	189	222	-	-	180

3. Experimental Program and Results

The experiments on the AISI 304 are focused on the identification of the yield strength, ultimate strength, percent elongation, Vickers hardness and fatigue properties expressed by *S-N* curves. The sizes and shapes of base metal coupons were in accordance with ASTMs [16-19], examples of specimens are shown in Fig. 2.

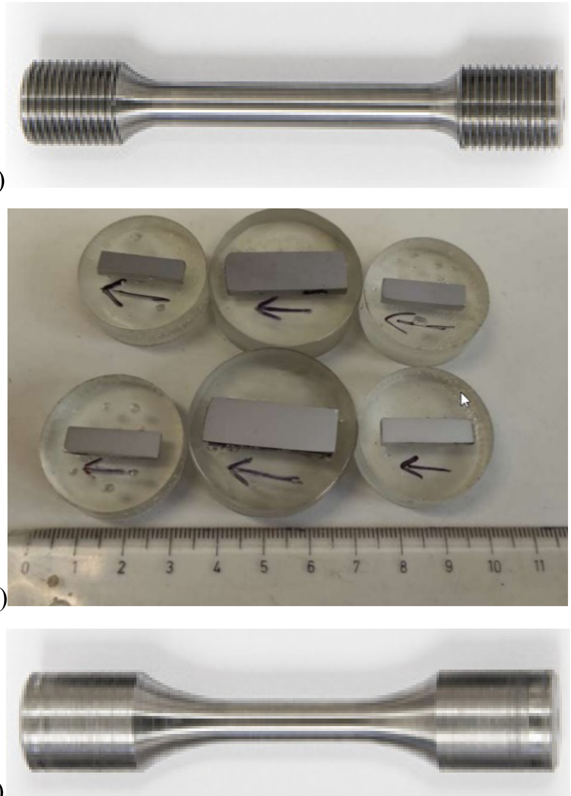
a)
b)
c)


Fig. 2: Examples of specimens used for experimental campaign performed on AISI 304: a) tensile test specimen, b) specimens for Vickers hardness test and c) specimen for fatigue test.

3.1. Tensile tests

In any structural engineering design, ultimate tensile strength and 0.2 offset yield strength are of particular importance. To be able to monitor changes in the value of material properties, the tensile tests at room temperature were performed on five smooth round bar specimens for all studied materials extracted from structural components. Specimens were tested by using a 50 kN hydraulic testing machine (Screw driven testing machine ZWICK Z50) meeting the ASTM E8/E8M-13 standard [16]. Test results are presented as engineering stress–strain diagrams (σ-ε) by using average values from 5 measurements. The σ-ε diagrams for given structural elements marked: L, D, PL-10, PL-20 and S are shown in Fig. 3. The average tensile properties of AISI 304 steels are summarized in Tab. 3. - ultimate tensile strength, 0.2 offset yield strength and elongation.

The tensile tests indicate that the strength properties of PL-10 and PL-20, Tab. 3. – Standard deviation, are inhomogeneous across the bar cross-section. The specimens, usually characterizing the material near the bar surface exhibit higher strength than the curves describing the behaviour of the material inside the bar due to technology preparation of building elements, see e.g. [19].

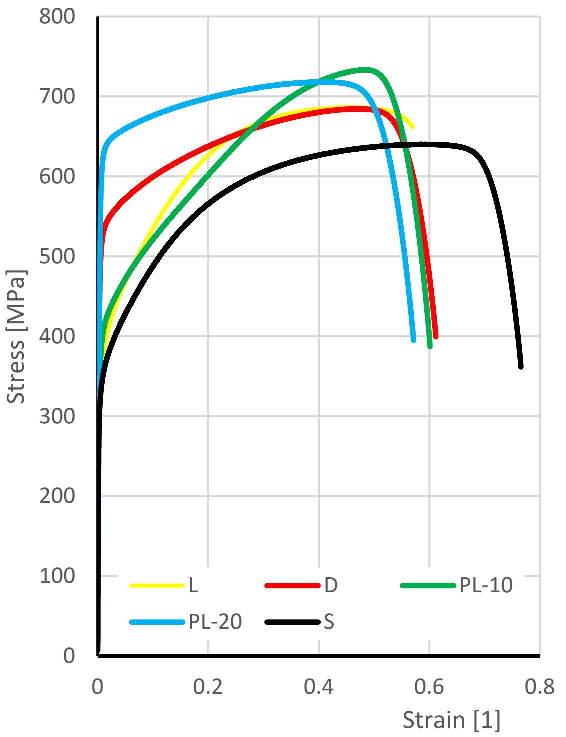


Fig. 3: True stress-strain mean curves for given structural elements (L, D, PL-10, PL-20 and S)

Tab. 3: The average tensile properties of AISI 304 steels made from structural elements L, D, PL-10, PL-20 and S at 25°C.

AISI 304	L	D	PL-10	PL-20	S
R_m [MPa]	**687**	**682**	**740**	**756**	**639**
Standard deviation	5.95	2.91	50.49	50.49	2.88
Standard deviation in %	0.86	0.42	6.67	6.67	0.45
$R_p = 0.2$ % [MPa]	**339.64**	**476.72**	**626.16**	**626.15**	**301.08**
Standard deviation	6.85	8.17	80.80	80.81	24.44
Standard deviation in %	2.01	1.71	12.9	12.90	8.11
Elongation [%]	**45.28**	**48.38**	**39.71**	**39.71**	**57.79**
Standard deviation	1.17	1.01	1.125	1.22	1.40
Standard deviation in %	2.60	2.42	2.85	2.95	2.42

3.2. Vickers Hardness determination

The samples for indentation tests were grinded and polished by conventional metallographic methods. The Vickers hardness [17] was determined in a standard way on a microhardness tester DuraScan 70 G5 with pyramid shaped diamond indenter with an apical angle of 136°. The indentations were measured in both axis from tip to tip. An example of an indentation is shown in Fig. 4. The average d of the two axis measurements was converted into the Vickers Hardness by the formula:

$$HV = \frac{F}{A} \approx \frac{1.8544F}{d}, \quad (1)$$

where *HV* is the Vickers HV (kgf/mm^2) *F* is the compressive load (kgf), *A* is the surface area of the indentation, and *d* is mean value of diagonal length d_1 and d_2 in millimetres. The results of measurement are summarized in Tab. 4. Similar values for austenitic steels can be found in [20].

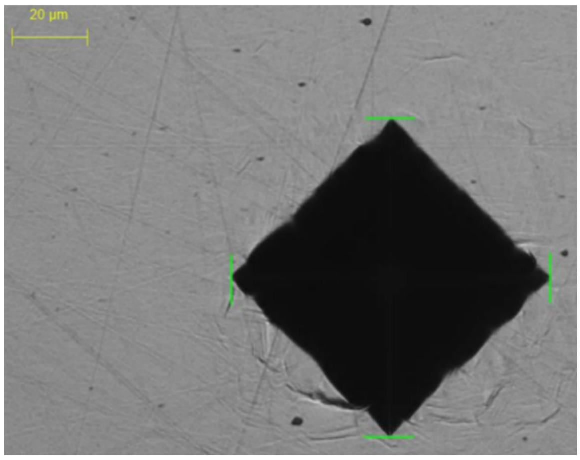


Fig. 4: Light microscope image of Vickers indentation. Loading force 1N

Tab. 4: Vickers hardness of investigated materials from AISI 304 structural elements (L, D, PL-10, PL-20 and S).

AISI 304	L	D	PL-10	PL-20	S
HV(0.1)	228.4	251.4	250.0	241.4	195.0
Standard deviation	11.28	7.28	22.8	11.28	6.00
Standard deviation in %	4.94	2.90	9.12	4.67	3.07

3.3. Fatigue properties S-N Curve

All the mentioned AISI 304 profiles have very wide use in mechanical and civil engineering. In that way, for example, applications of AISI 304 can be associated to areas such as bridges, cranes, high loaded structures, etc. The fatigue properties play important role in design of structures. Therefore, the Wöhler (*S-N*) curves are introduced for fatigue analysis. Based on the results of the tensile test, the high-cycle fatigue life of specimens was tested using different stress levels to obtain AISI 304 for PL-20 and S fatigue life point diagram and a preliminary *S-N* curve. Three specimens were tested under reducing stress levels, until the loading cycles reached 10^7 times which is regarded as the fatigue limit. The loading frequency *f* of fatigue testing machine (Servohydraulic system Zwick/Roell Amsler HC25, push-pull) was set as 20 Hz, while cyclic loading stress ratio (R = 0.1) was the sine wave. The ambient temperature was 25±2 °C. The corresponding *S-N* (Wöhler) curves are a plot of the magnitude of an alternating stress versus the number of cycles to failure for a selected S and PL-20 materials, in Fig. 5. Typically, the stress is display in normal scale and number of cycles is displayed on logarithmic scale.

For evaluation of fatigue data was applied the Basquin's law [21] in the form:

$$\sigma_a = AN_f^B, \quad (2)$$

where the coefficients *A* and *B* of the relation (2) are the coefficients of fatigue strength in one cycle and exponent of fatigue strength, the advance probabilistic evaluation of *S-N* curves can be found in [22-25].

The values of the Basquin's model for S and PL-20 AISI 304 are presented in Tab. 5, together with fatigue strength in N=1×10^7.

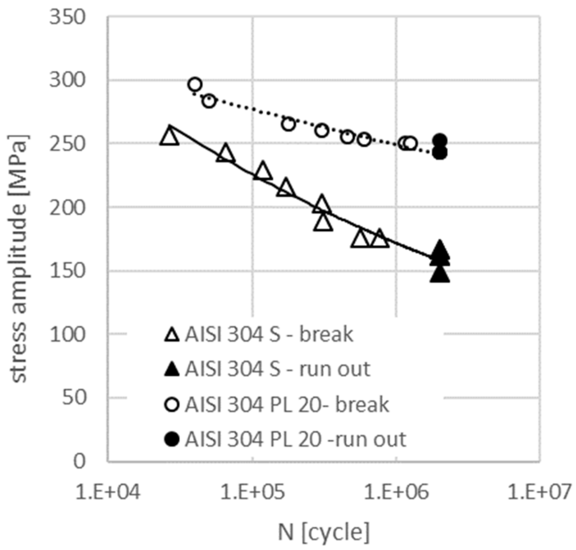


Fig. 5: AISI 304 fatigue performance by *S-N* (Wöhler) curves for R = 0.1: material from structural elements S and PL-20

Tab. 5: Coefficients of the Basquin's law relation (2) and the fatigue limit together with index of dispersion of selected materials from AISI 304 structural elements PL-20 and S.

AISI 304	*A*	*B*	R^2	σ_f [MPa]
S	890	-0.119	0.95	162
PL-20	470	-0.046	0.94	243

4. Discussion

According to ISO 18265-2003, the Vickers hardness can be recalculated to ultimate tensile strength R_m (HV 0.1). In Tab. 6, the comparison of calculated and experimentally determined values is presented. The tensile properties of the PL-20 were partially better than the rest of studied bars, but with high values of relative standard deviation 6.67 %; this is in accordance with HV 0.1 measurements.

Tab. 6: Comparison of AISI 304 properties for different structural elements (L, D, PL-10, PL-20 and S). of investigated materials from AISI 304.

AISI 304	L	D	PL-10	PL-20	S
HV0.1	228.4	251.4	250.0	241.4	195.0
R_m (HV 0.1) [MPa]	**732**	**804**	**800**	**773**	**625**
R_m [MPa] average	**687**	**682**	**740**	**756**	**639**

The absolute fatigue strengths $\Delta\sigma$ of the higher steel grades remain definitely larger those of lower steel grades, as can be observed from the absolute fatigue strength values. In studied materials from S and PL-20 profiles, the absolute fatigue values are 57% ($=2*\sigma_c/(1-R)/R_m*100=2\times162/0.9/639*100$) and 71% ($=2*\sigma_c/(1-R)/R_m*100=2\times243/0.9/756*100$), respectively. The profile PL-20 has similar fatigue response, like S235J2 (72%) mentioned in [26].

5. Conclusion

Mechanical properties of five various profiles made from austenitic steel AISI 304 were experimentally determined and compared with properties specified by producers. The following conclusions can be drawn.

- The tensile properties through cross section change a lot (especially 20×60 mm), but the mechanical values are never lower than specified by material list of producers.
- The Vickers hardness HV 0.1 of the investigated stainless steels elements ranges from 195 to 251.4 and it is in relation to the tensile properties of the material.
- The fatigue limit/strength expressed by stress amplitude for the selected profiles under stress ratio R = 0.1 is from 162 to 243 MPa.
- Despite the fact that the tested bars meet the strength standards, it is advisable to perform an indicative hardness measurement on the material used for a reliable design of the structure.

Note that, a method to predict the fatigue limit by using Vickers hardness measurements was proposed by Casagrande et al. in [27]. Next step will be calibration of AISI 304 results by Vickers method on predicted fatigue limit.

Acknowledgements

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