

CYCLIC STRESS-STRAIN CURVES

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CYCLIC STRESS-STRAIN CURVES

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FOREWORD

The report develops rules for determination of cyclic stress-strain curves for materials contained in the ASME Boiler and Pressure Vessel Code (BPVC), Section II, Tables IID from monotonic data. The following classes of materials were considered:

- Carbon steel (all strength levels)
- Chromium Molybdenum (Vanadium) steels (i.e., 1.25Cr-1Mo or 2.25 Cr-1Mo), including enhanced alloys (all strength levels)
- Ferritic-martensitic steels (e.g., 9-12% Cr), including enhanced alloys
- Stainless steels (austenitic, ferritic-martensitic, duplex, precipitation hardening)
- Nickel-base alloys (e.g., N06600, N06625, N08800).
- Aluminum based alloys
- Titanium based alloys
- Copper based alloys
- Zirconium based alloys

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SUMMARY

Monotonic strength values of materials like Yield Strength or Ultimate Tensile Strength are usually determined with well-defined and well-established testing equipment and sample geometries. For many materials, a wide database exists which accelerates statistical analyses and determination of minimum values, however, cyclic stress-strain curves do not benefit from such an established knowledgebase. Fatigue testing is much more complex than tensile testing, and different approaches exist in determining the representative hysteresis loop.

Figure S-1: Proposed procedures for determination of cyclic stress-strain curves for different materials

	Conservative	Average	Comments
Carbon steels	YS'=YS for YS≤ 350 MPa YS'=average for YS>350 MPa	YS'=f1(YS) n'= 0.167	Results compare well with literature
Low alloy steels	YS'=YS for YS≤ 400 MPa YS'=average for YS>400 MPa	YS'=f2(YS) n'= 0.130	Results compare well with literature
Martensitic 9-13% Cr	YS'=average	YS'=f3(YS) n'= 0.116	Results compare well with literature
Austenitic steels	YS'=YS	YS'=f4(YS _{RT} , T) n'=f5(T)	Temperature is important
Nickel-base alloys	YS'=YS	YS'=f6(YS) n'= 0.150	Results compare well with literature
Aluminum alloys	YS'=YS	YS'=YS for high strength temper (T4, T6) YS'=f7(YS) for other alloys n'= 0.086	
Titanium alloys	YS'=average	YS'= f8(YS) n'= 0.085	Only limited amount of data available
Copper and Zirconium alloys	N.A.	N.A.	Not sufficient data available

Notes: YS=Yield stress, YS'=Cyclic yield stress, n'=cyclic strain hardening exponent, $YS'=K' \cdot 0.002^{n'}$, f_i (i=1-8). Material dependent functions are derived in the body of this report.

Cyclic stress-strain curves can therefore be only considered as an average description of a material.

As materials can cyclic soften and cyclic harden, the relationship between monotonic and cyclic yield strength is of particular importance. The cyclic stress-strain curve for strain-controlled fatigue near zero mean stress is usually described by the following relationship:

$$\frac{\Delta \varepsilon}{2} = \frac{\Delta \sigma}{2E} + \left(\frac{\Delta \sigma}{2K'} \right)^{\frac{1}{n'}}$$

Where:

$\Delta \varepsilon$ =total strain range, $\Delta \sigma$ =(representative) total stress range, E=Young's modulus, K'=cyclic strength coefficient, n'=cyclic hardening exponent.

The cyclic stress range usually changes as a function of a number of cycles (hardening/softening) and therefore a “typical” stress range must be chosen. By convention, the stress range at $N_f/2$ is used in almost all cases. Other definitions are occasionally used, but in this report the $N_f/2$ approach is used almost exclusively.

K' (YS') and n' were determined by analysis of literature data for the different groups of materials. The results are summarized in Figure S-1. The procedures given are only valid for materials not hardened by cold deformation or yield stresses far outside the ASME code specifications. They should only be used for temperatures governed by time-independent properties. For higher temperatures, creep effects might impact the cyclic behavior. Within these limitations, it is possible to determine representative cyclic stress-strain curves for several materials presented in the ASME BPVC Section II Tables IID.

It is important to stress that, with this approach, only typical average values could be determined which allow an assessment of the cyclic response of a material (e.g., for J-integral assessments). Excel worksheets for monotonic and cyclic stress-strain curves were developed.

Raw data created during the project and literature used is also presented and discussed with respect to eventual implementation into the ASME Materials Database. In addition to the literature cited in the document, the References section contains all literature used to establish the results of this report.

Details are summarized in Appendices A-D:

- Appendix A: Description of the Excel Worksheet for determination of stress-strain curves
- Appendix B: Representation of cyclic data for eventual inclusion into the ASME database
- Appendix C: Example for inconsistencies once not well correlated monotonic and cyclic data are used
- Appendix D: Examples for validity of concept

Important Remarks:

In contrast to monotonic stress-strain curves, the procedure for determination of cyclic stress-strain curves is not very well established, and large differences between the results of different investigations exist. For this investigation, results from single-specimen tests were used, and the representative hysteresis loop was the loop at half lifetime.

The cyclic strains leading to fatigue failure are in the 1-2 percent range. Therefore, no discrimination between engineering and true stresses and strains is necessary.

The spreadsheet for evaluation of stress-strain curves is not part of the report.

Disclaimer:

Results gained with the introduced worksheet can only serve as technical information to assess materials properties. At the current stage they may not be used for any safety-relevant calculations or considerations.

1 INTRODUCTION AND DESCRIPTION OF THE PROBLEM

Cyclic stress-strain curves describe the stress-strain behavior under cyclic loads. Usually, the cyclic stress amplitude $\Delta\sigma/2$ is plotted as a function of the cyclic strain amplitude $\Delta\varepsilon/2$ for a defined cycle. The fact that the stress-strain response of a material is usually cycle-dependent requires a reference cycle which can be considered as representative for the cyclic stress-strain curve.

In contrast to monotonic stress-strain curves which deliver a unique relationship between the stress and strain of a material, the cyclic stress-strain relationships may undergo cycle-dependent changes. The material can be:

- Cyclic hardening
- Cyclic softening
- Cyclic stable
- Combinations of cyclic softening and cyclic hardening

This means that the stress-strain relationship determined in strain fatigue tests is usually cycle dependent. Figure 1-1 shows the change of stress amplitude with a number of cycles for a low carbon steel as an example [1].

Figure 1-1: Cyclic hardening-softening curves of a low carbon steel for different total strain amplitudes, ε_a . (Replotted from [1])

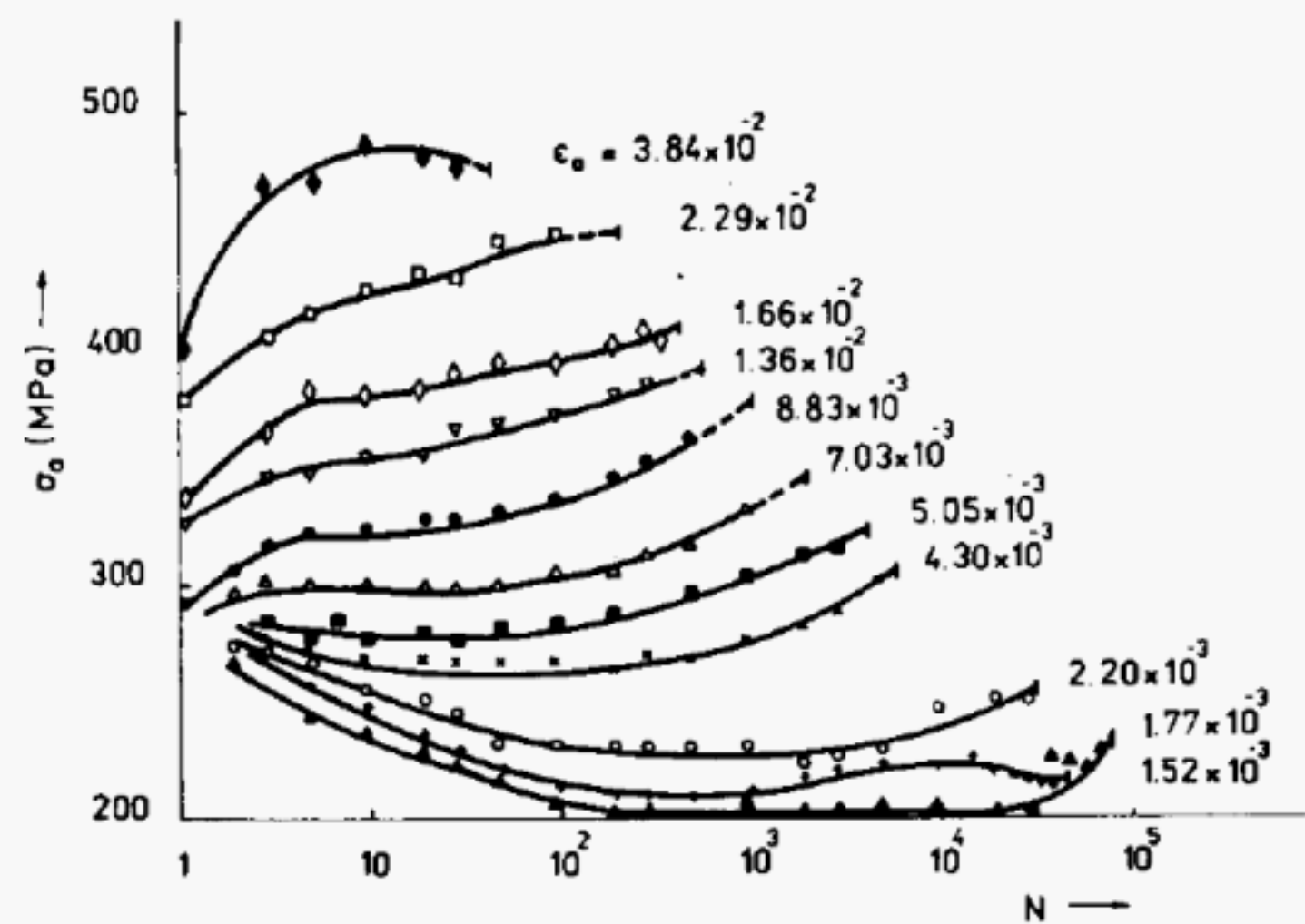


Figure 1-2 shows the cyclic stress-strain response of IN 600 at a different number of cycles (replotted from [2]).

Figure 1-2: Cycle dependence of stress-strain curves for IN 600 (replotted from literature [2])

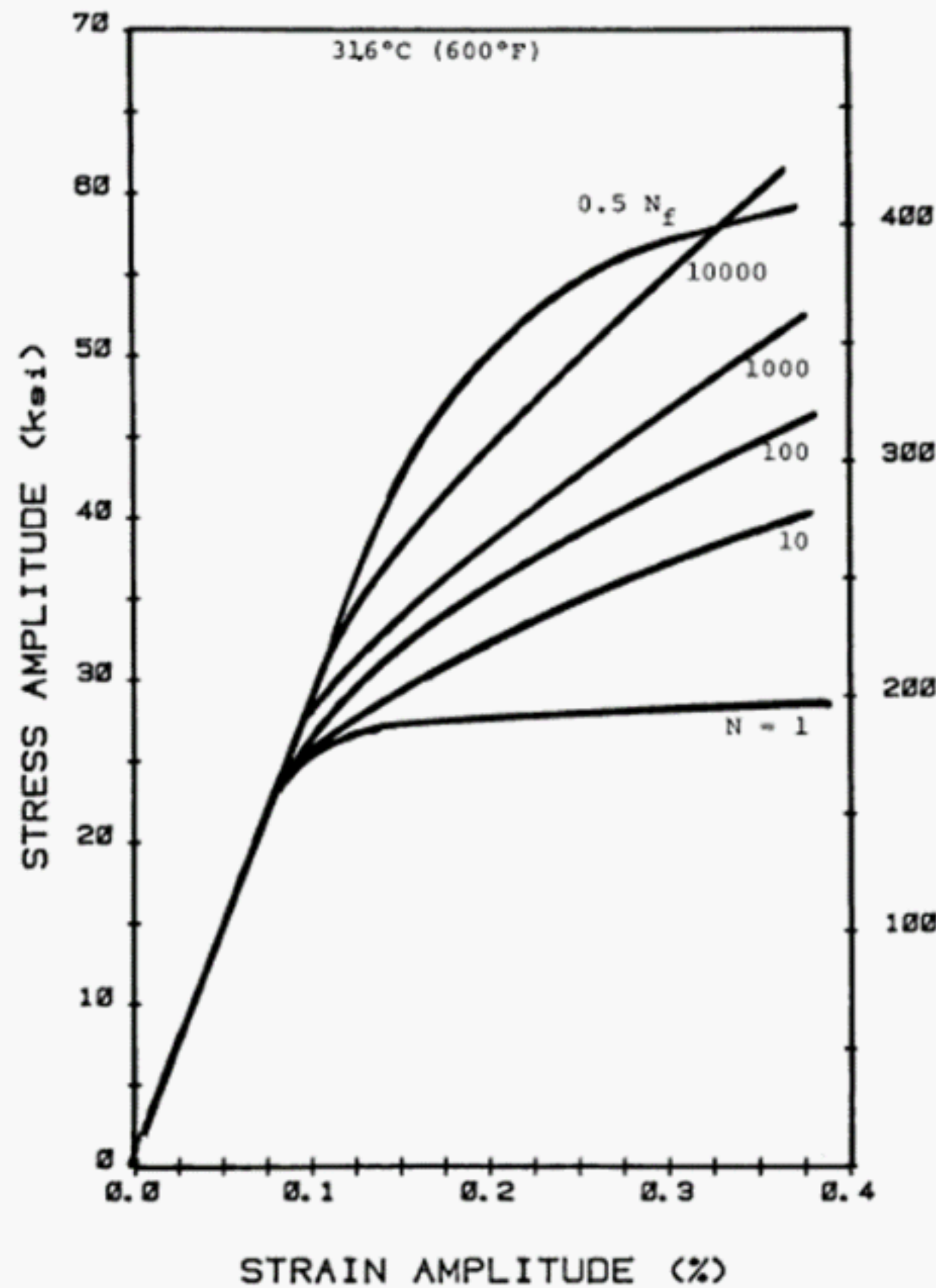


Figure 3-16. Cyclic stress strain curves for Alloy 600 at 316°C at 1/4, 10, 100, 1000, 10,000 cycles and midlife.

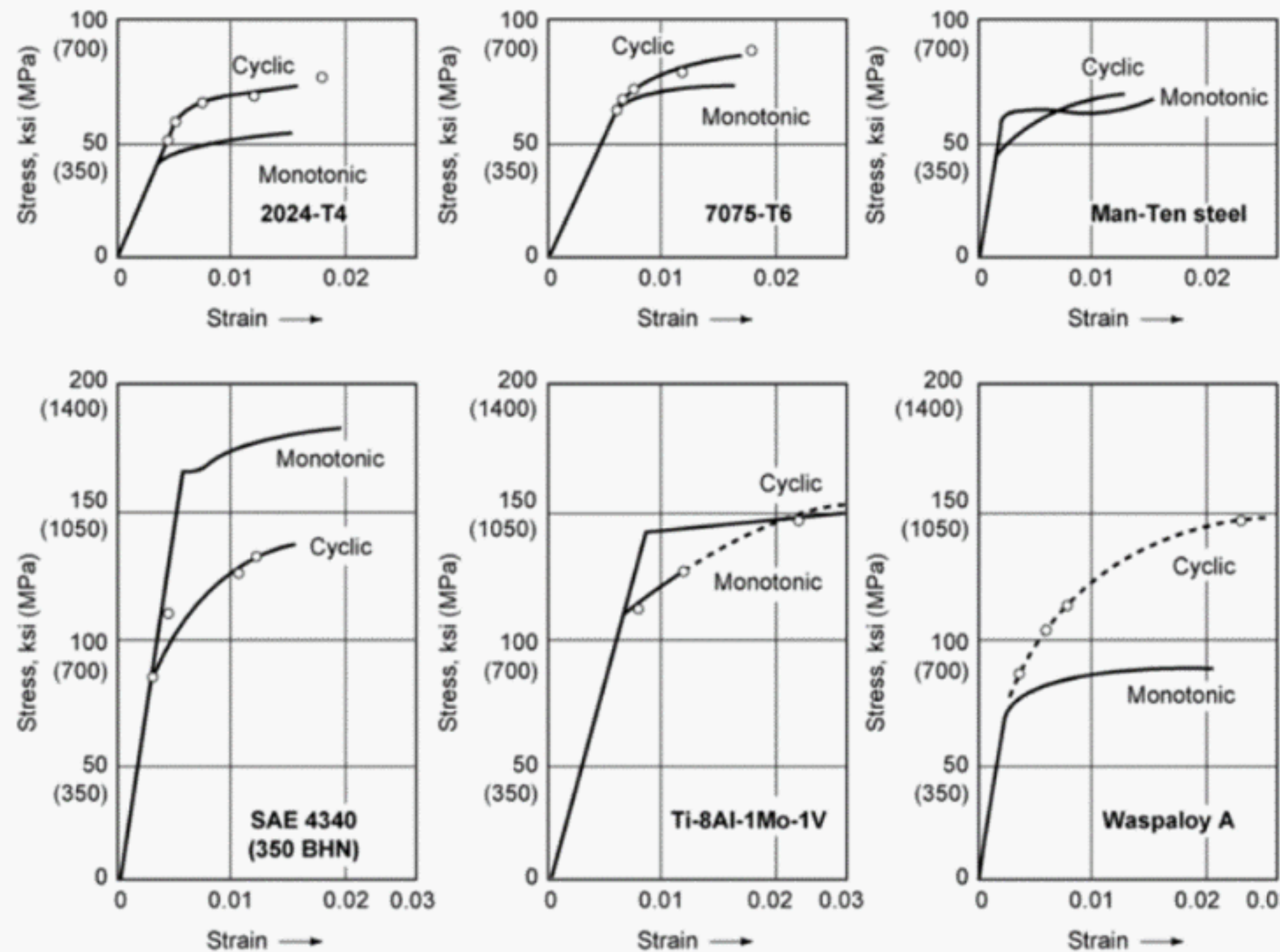
When a cyclic stable hysteresis loop is obtained, this stabilized loop can be used as a reference. If a cyclic stable hysteresis loop is not established, the cycle at half the time to rupture ($N_f/2$) is taken as a reference independent of whether the material is cyclic softening, cyclic hardening or shows a mixed behavior. These cycles are usually obtained from reversed strain cycling tests on a number of companion specimens, but shortcut procedures are also used by various investigators. Such shortcut methods use only a single specimen, which is cycled a certain number of times or until saturation is reached. The levels of cyclic straining are stepwise increased (incremental step test). This means that cyclic pre-deformed samples are used, which can lead to artifacts in cases where cycle-dependent microstructural changes can happen. It is also worth mentioning that low cycle fatigue (LCF) is primarily crack growth from short cracks, which can also affect the behavior of pre-deformed material. The fact that materials can cyclically harden or soften makes the relationship between cyclic and monotonic curves important.

A cyclic stress-strain curve alone, without any relation to the monotonic properties, is only of very limited use for design or safety considerations.

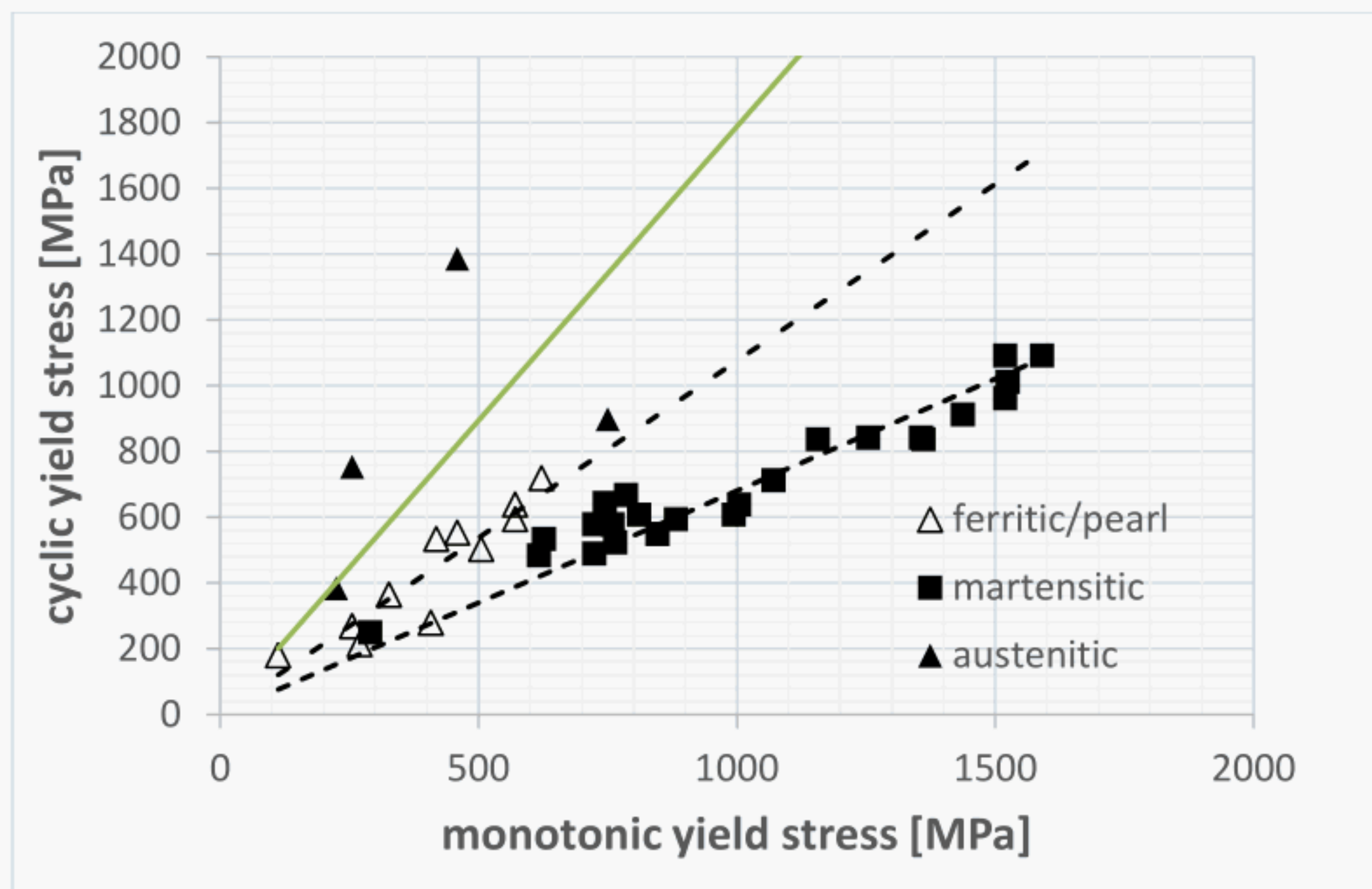
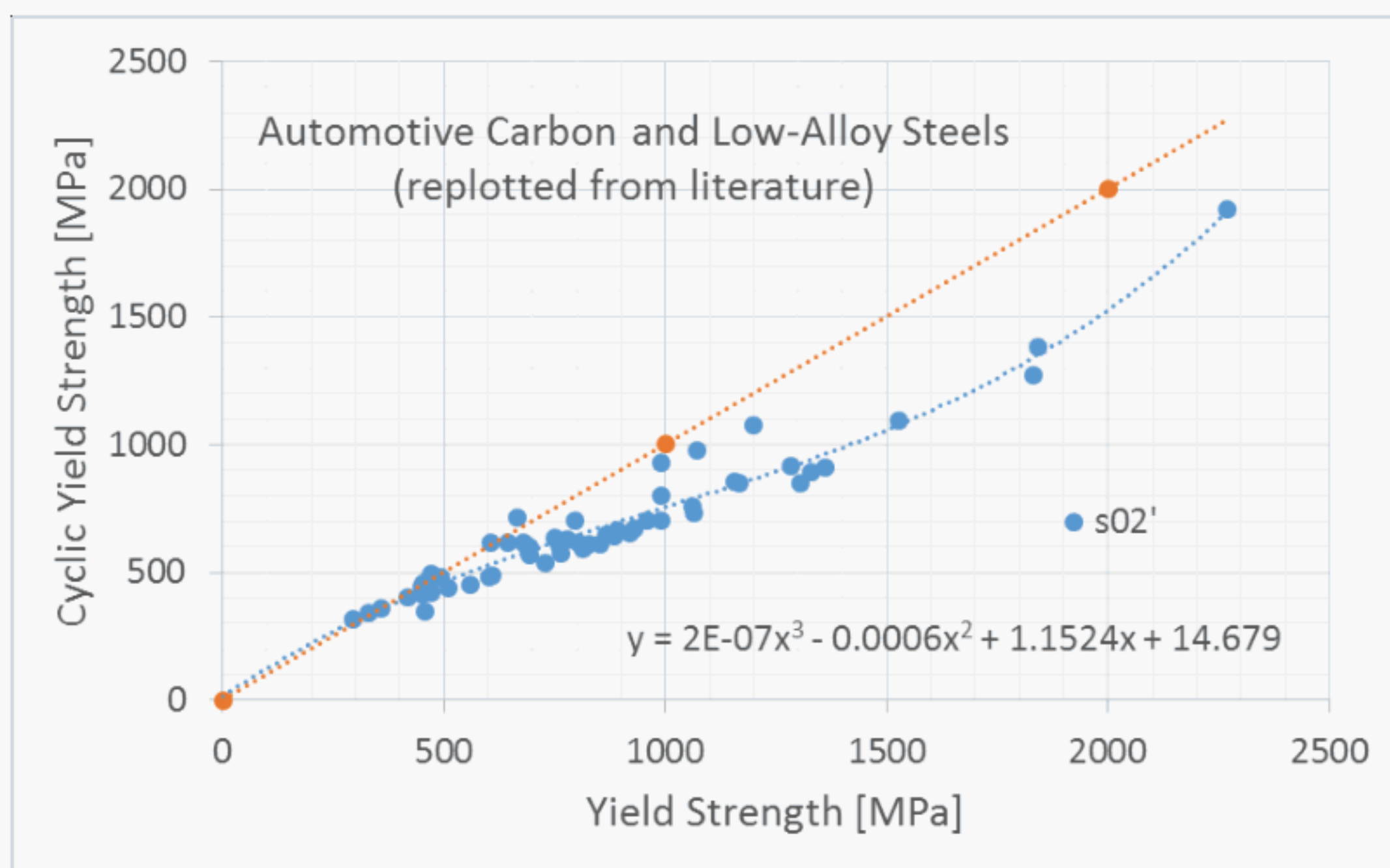
An independent choice of a cyclic stress-strain curve without reference to the monotonic behavior might cause misleading results. Cyclic softening material can appear as cyclic hardening and vice-versa (an example from ASME BPVC Section VIII/2 is given in Appendix C:). Therefore, relationships between

monotonic and cyclic properties are required. General trends for cyclic hardening/softening of different classes of materials are given in [3]. Figure 1-3 illustrates typical examples of monotonic and cyclic stress-strain curves. Austenitic matrices tend towards cyclic hardening, whereas ferritic/martensitic materials tend towards cyclic softening.

Figure 1-3: Monotonic and cyclic stress-strain diagrams for six different engineering alloys. ○, companion specimens; solid line, incremental step (source [3])



A few attempts for the derivation of cyclic stress-strain curves exist (e.g., [4], [5], [6]). Particularly, the relationships between monotonic and cyclic yield strengths were analyzed in these investigations. Results are shown in Figure 1-4 and Figure 1-5. Figure 1-4 shows data for ferritic/pearlitic, martensitic, and austenitic steels. Ferritic/pearlitic steels tend to behave cyclic stable to slight cyclic softening. The martensitic steels are cyclic softening. Austenitic steels show cyclic hardening behavior, however, a wide scatter of data can be seen. This will be further discussed in section 7 concerning austenitic steels. The results shown in Figure 1-5 indicate that carbon and low alloy steels start cyclic stable at low yield strength and become cyclic softening at high yield strength. These results will also be discussed later in the report.

Figure 1-4: Correlation between monotonic and cyclic yield strength for different alloys [4]**Figure 1-5: Correlation between monotonic and cyclic yield strength of carbon and low alloy steels used in automotive applications at room temperature [6]**

The exact shape of the cyclic curves depends on the material itself and its response to deformation (e.g., dynamic strain aging, deformation induced martensite, prior cold working, deformation rates at elevated temperatures).

2 EXPERIMENTAL PROBLEMS WITH DETERMINATION OF CYCLIC STRESS-STRAIN CURVES

Cyclic stress-strain curves are usually represented in Ramberg-Osgood form:

$$\frac{\Delta \varepsilon}{2} = \frac{\Delta \sigma}{2E} + \left(\frac{\Delta \sigma}{2K'} \right)^{\frac{1}{n'}}$$

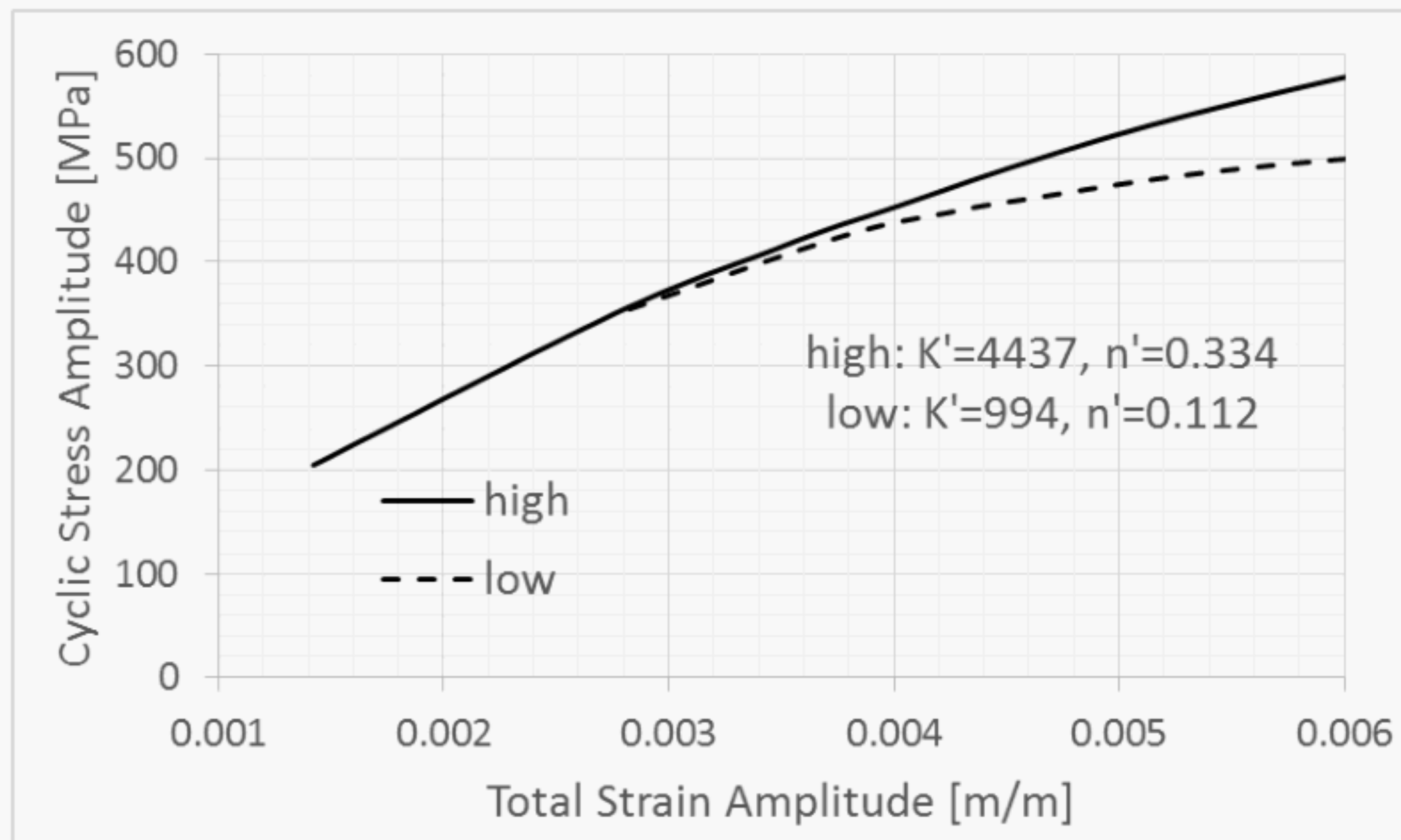
The total strain (elastic + plastic strain) can be represented by the elastic portion and a power law function for the plastic part. The coefficient K' and the exponent n' are material-dependent constants.

From the determination of cyclic stress-strain curves, an extremely high scatter can be expected, which is only partly due to the material itself. The main source of scatter is the performance of fatigue tests. This assessment is based on the experience of the author who led a group on LCF and creep at BBC/ABB Switzerland:

- Many data given in the literature were created in the 1960s and 1970s, just when suitable testing equipment was becoming available
- A stiff and extremely well-aligned testing machine must be available (particularly during the compression phase of the tests)
- Sometimes tests are reported with displacement control (instead of strain control)
- Sample geometry and strain measurements: hourglass-samples with diametric strain measurements (mostly one gage only) are compared with dog-bone type samples and mostly 2 strain gages getting the signals from the movement of the shaft of the samples. Sometimes also scissor gages are (were) in use.
- Only a limited number of tests are performed, making the determination of the power law coefficient and exponent very uncertain
- Different ways of determination of the cyclic stress-strain curve (companion sample, incremental step, etc.)

Such experimental deficiencies are a main reason for the wide scatter and differences in experimental results. Large differences can occur particularly when the experimental data were gained from tests performed at relatively low strain ranges. Figure 2-1 compares two cyclic stress-strain curves for the same material under comparable conditions.

Figure 2-1: The influence of very different K' and n' values on the calculated cyclic curves at low strain amplitudes (typical for LCF loading)



Although the experimentally determined constants (K' and n') differ by factors of more than four and three, respectively, the curves compare at least reasonably well in the considered strain range. For larger strains the curves would differ significantly. Following the rule of thumb that a strain range of 1 percent corresponds with about 1,000 cycles to failure, it can be expected that technically relevant cyclic stress-strain curves seldom exceed a total strain range of 2-3 percent.

3 AIM OF THE PRESENT REPORT

It is the aim of this report to develop rules for determination of cyclic stress-strain curves for materials contained in ASME BPVC Section II Tables IID from monotonic data. It is clear that the results can only meet the requirements on an average basis. However, bearing in mind the uncertainties concerning determination of cyclic stress-strain curves, this can be considered a technically acceptable solution.

Cyclic stress-strain curves are represented in Ramberg-Osgood form:

$$\frac{\Delta\epsilon}{2} = \frac{\Delta\sigma}{2E} + \left(\frac{\Delta\sigma}{2K'}\right)^{\frac{1}{n'}}$$

For determination of K' and n' the following procedure was chosen:

- (a) A relationship (often polynomial) between monotonic yield stress and cyclic yield stress was established using literature data for each class of materials.
- (b) An average value for n' was determined using literature data.
- (c) K' was determined according to the relation: $K' = YS' / (0.002)^{n'}$
- (d) This procedure worked for all materials with the exception of austenitic steels, where an approach based on temperature dependence of YS' was used.

The following classes of materials were considered:

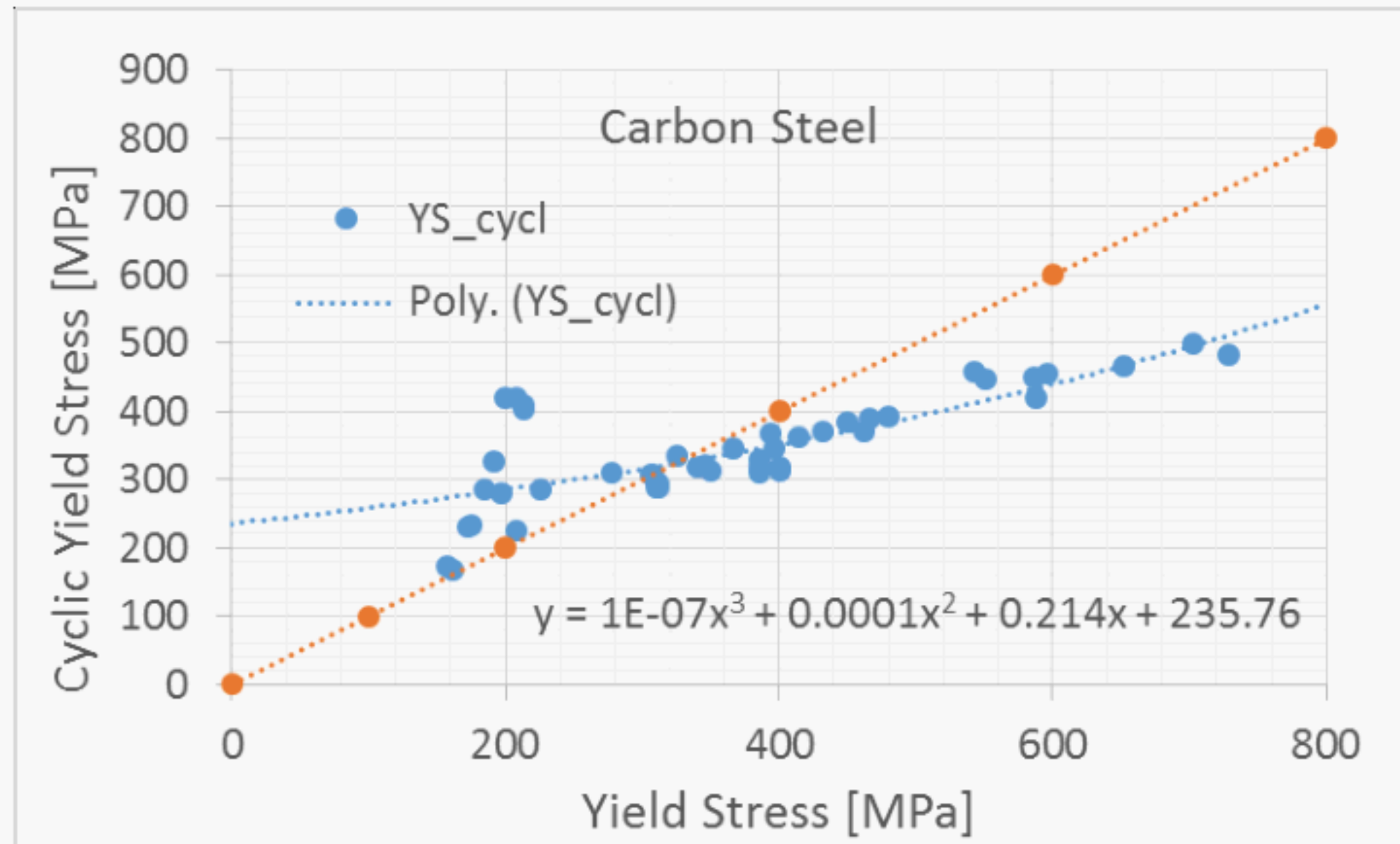
- Carbon steel (all strength levels)
- Chromium Molybdenum (Vanadium) steels e.g. 1.25Cr-1Mo or 2.25 Cr-1Mo, including enhanced alloys (all strength levels)
- Ferritic-martensitic steels (e.g., 9-12% Cr), including enhanced alloys
- Stainless steels (austenitic, ferritic-martensitic, duplex, precipitation hardening)
- Nickel-base alloys (e.g. N06600, N06625, and N08800).
- Aluminum based alloys
- Titanium based alloys
- Copper based alloys
- Zirconium based alloys

As typical low-cycle fatigue deformations seldom exceed a total strain range of 2-4 percent, cyclic stress strain curves remain limited to the "low strain" regime and a simple power law approach can be used also for correlation between true cyclic strain and true cyclic stress. The yield stress ($Y-1$) is thereby considered as central scaling property. Monotonic and cyclic curves for several materials could be derived from Table IID data.

4 CARBON STEELS

Figure 4-1 illustrates the dependence of the cyclic yield stress from the monotonic yield stress. The material is cyclic indifferent or cyclic hardening up to a monotonic yield stress of about 350 megapascals (MPa). For higher yield strengths, carbon steels start cyclic softening.

Figure 4-1: Relation between monotonic and cyclic yield stress for carbon steels



When the material has a yield point, the yield strength might be relatively high and a mixed behavior (softening at lower strains/hardening at higher strains) can occur [3]. A third-order polynomial was chosen as a best fit of the data.

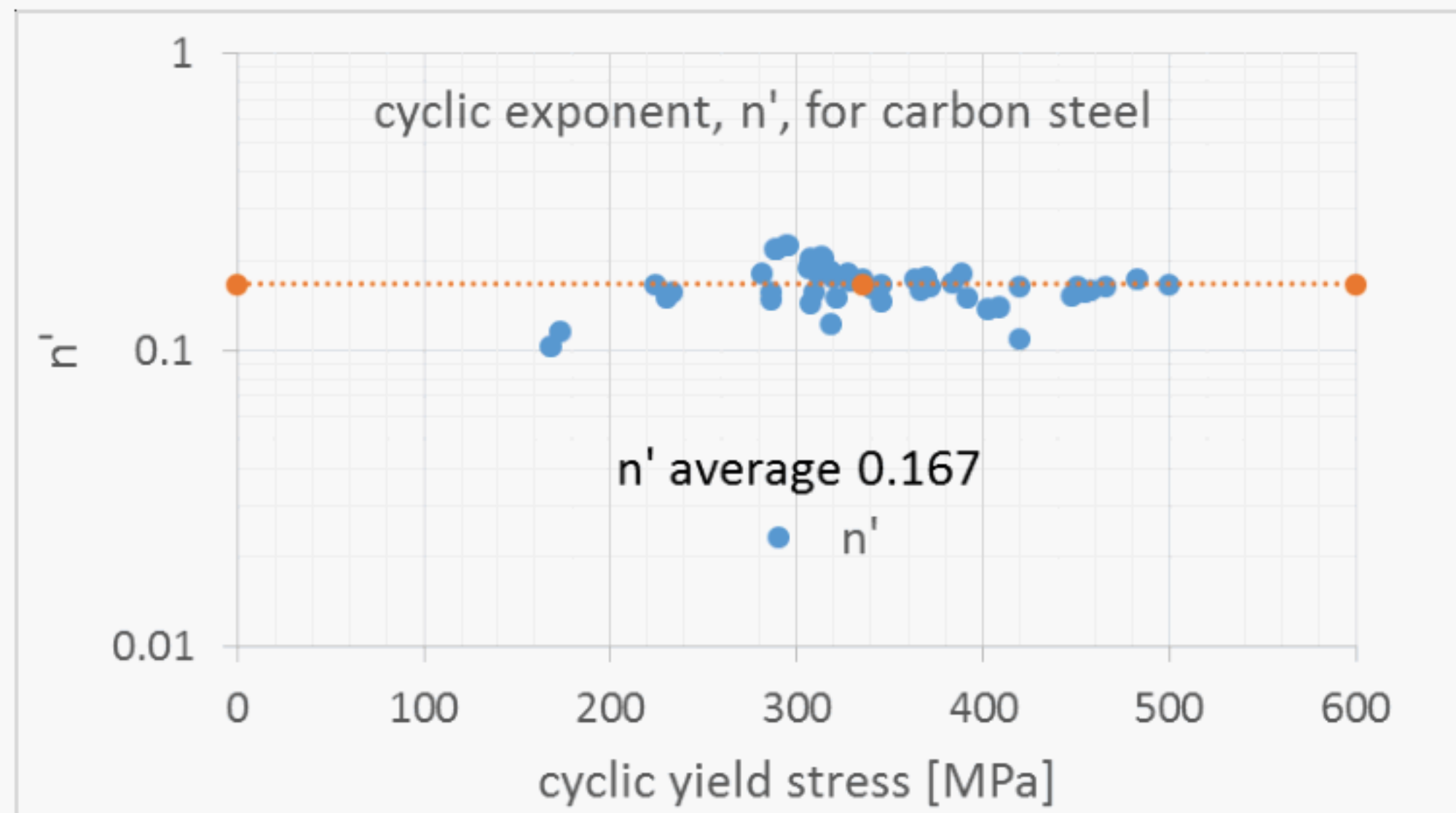
$$YS' = a_1 * YS^3 + a_2 * YS^2 + a_3 * YS + a_4$$

Where:

$$\begin{aligned} a_1 &= 1.19E-07 \\ a_2 &= 1.39E-04 \\ a_3 &= 2.14E-01 \\ a_4 &= 2.36E+02 \end{aligned}$$

An average value of the cyclic hardening exponent of 0.167 (independent from the yield strength) was found and is illustrated in Figure 4-2.

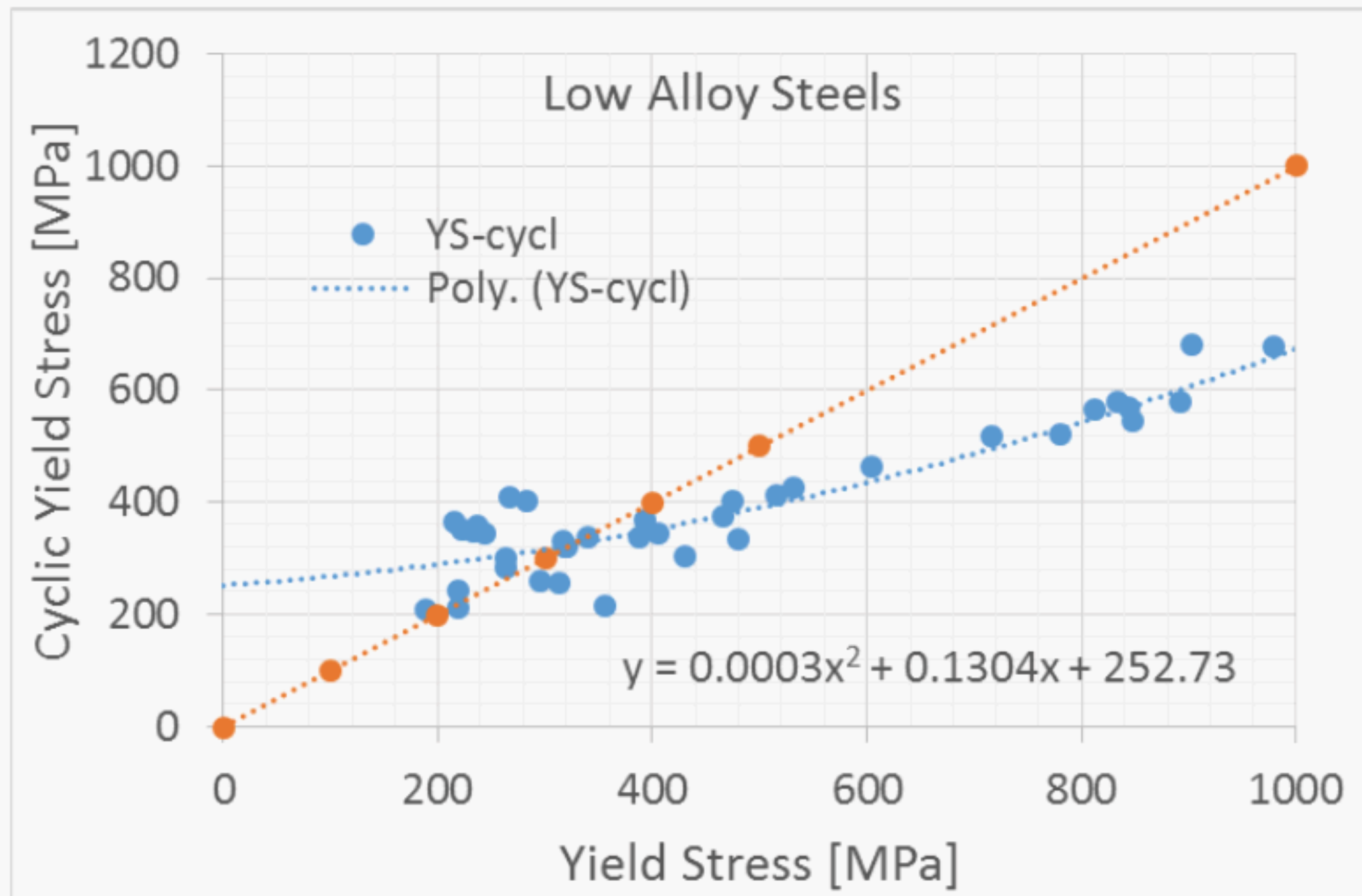
Figure 4-2: Cyclic hardening exponents for carbon steels



5 LOW ALLOY STEELS

For low alloy steels, the same procedure as for carbon steels was used. The results are shown in Figure 5-1 and Figure 5-2.

Figure 5-1: Relation between monotonic and cyclic yield stress for low alloy steels



A second order polynomial was chosen as best fit of the data:

$$YS' = b_1 * YS^2 + b_2 * YS + b_3$$

Where:

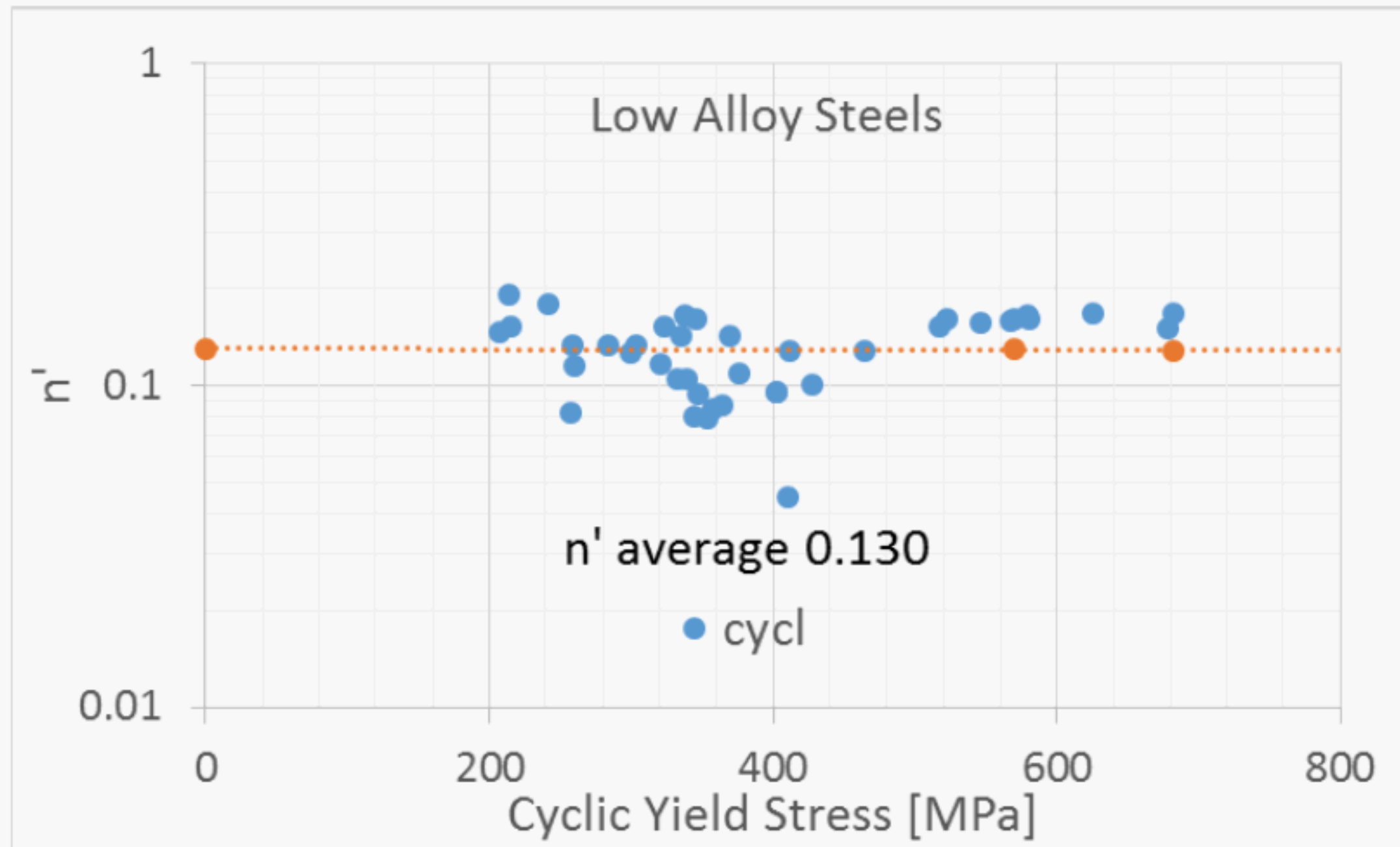
$$b_1 = 2.91E-04$$

$$b_2 = 1.30E-01$$

$$b_3 = 253$$

An average value of the cyclic hardening exponent of 0.130 (independent from the yield strength) was found and is illustrated in Figure 5-2.

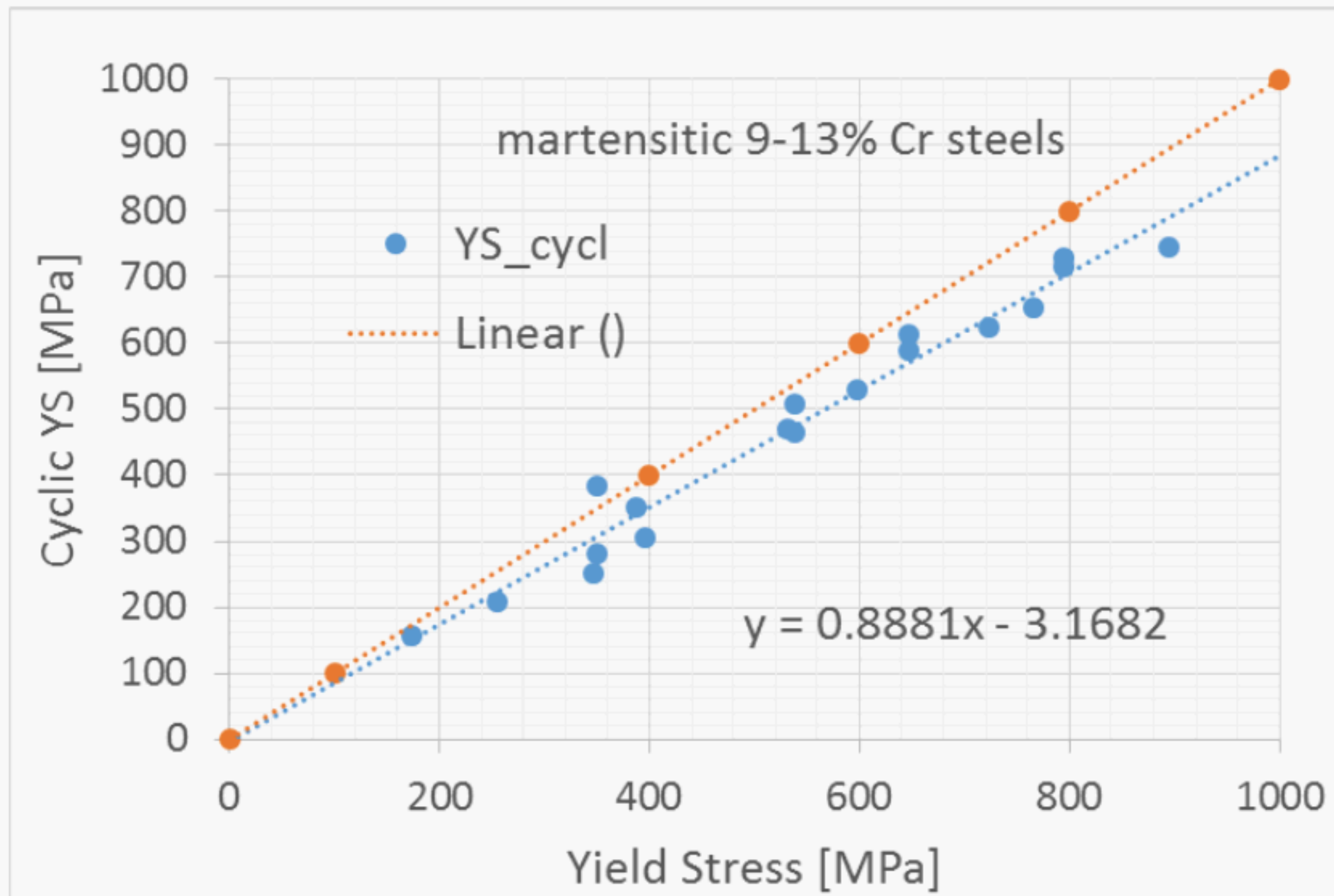
Figure 5-2: Cyclic hardening exponents for low alloy steels



6 MARTENSITIC 9-13% CR STEELS

For martensitic 9-13% Cr steels, softening was found throughout the entire range of yield stresses investigated and is illustrated in Figure 6-1.

Figure 6-1: Relation between monotonic and cyclic yield stress for low alloy steels

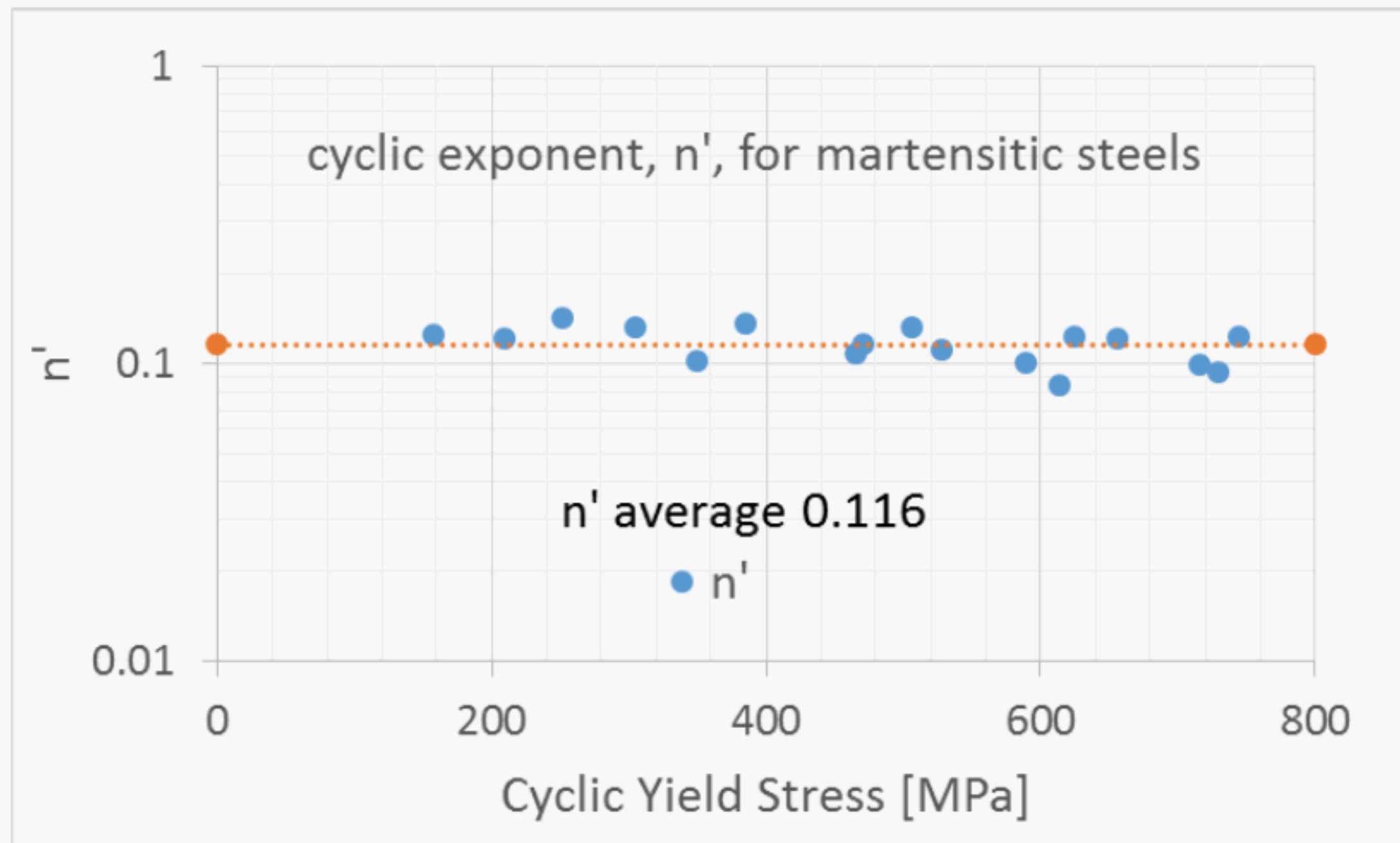


The data could be best described with a simple linear relationship:

$$YS' = 0.8881 \cdot YS - 3.1682$$

The cyclic hardening exponents were independent from cyclic yield stress. An average value of the cyclic hardening exponent of 0.130 (independent from the yield strength) was found and is illustrated in Figure 6-2.

Figure 6-2: Cyclic hardening exponents for martensitic 9-13% Cr steels



7 AUSTENITIC STEELS

Figure 7-1 demonstrates the relationship between monotonic and cyclic yield stress for austenitic steels. In contrast to the steels previously discussed, there exists no proper correlation between these two quantities. This is also in agreement with the data shown in Figure 1-4, where ferritic steels reported much less scatter than the austenitic steels.

Figure 7-1: Cyclic yield stress as a function of monotonic yield stress for austenitic steels

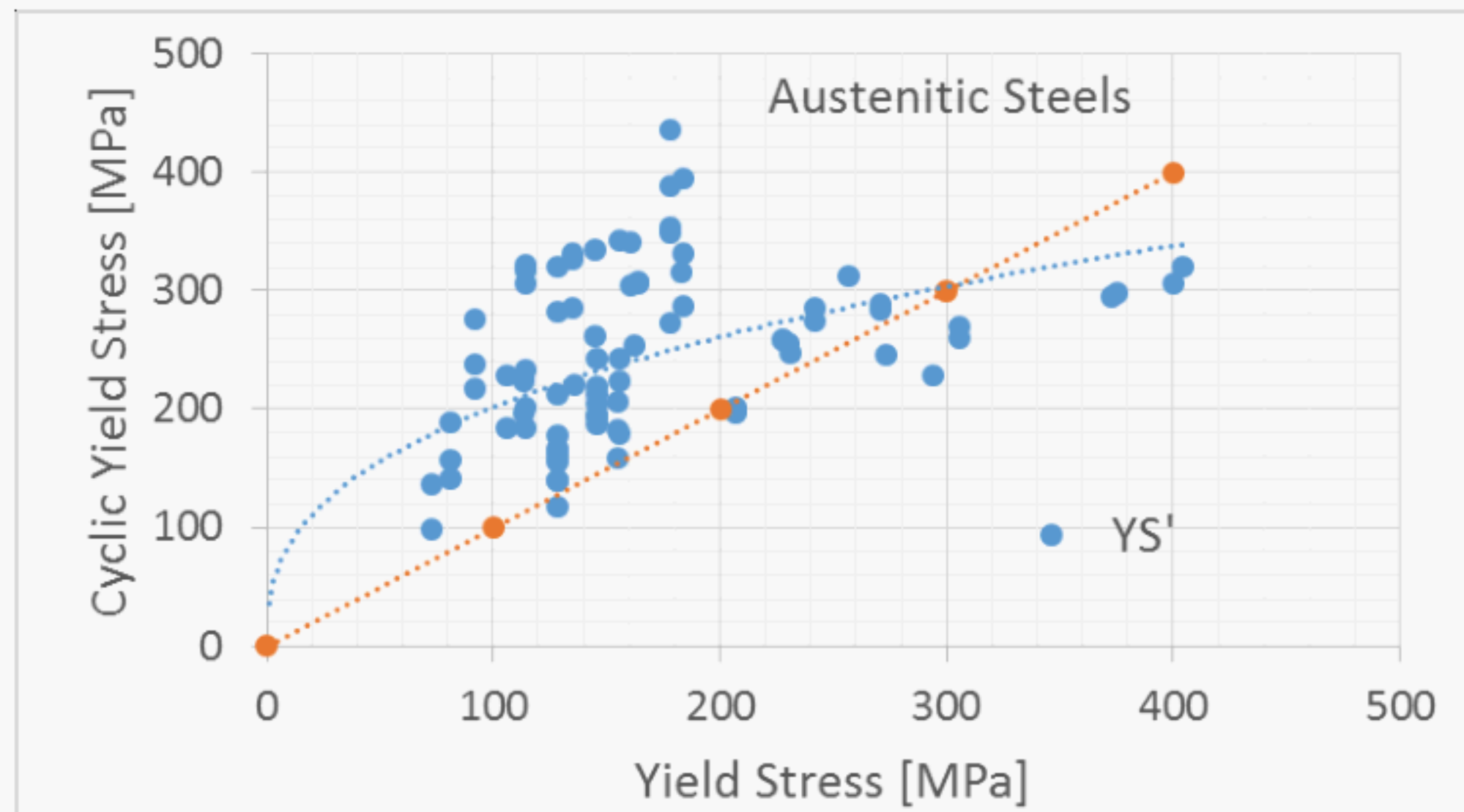
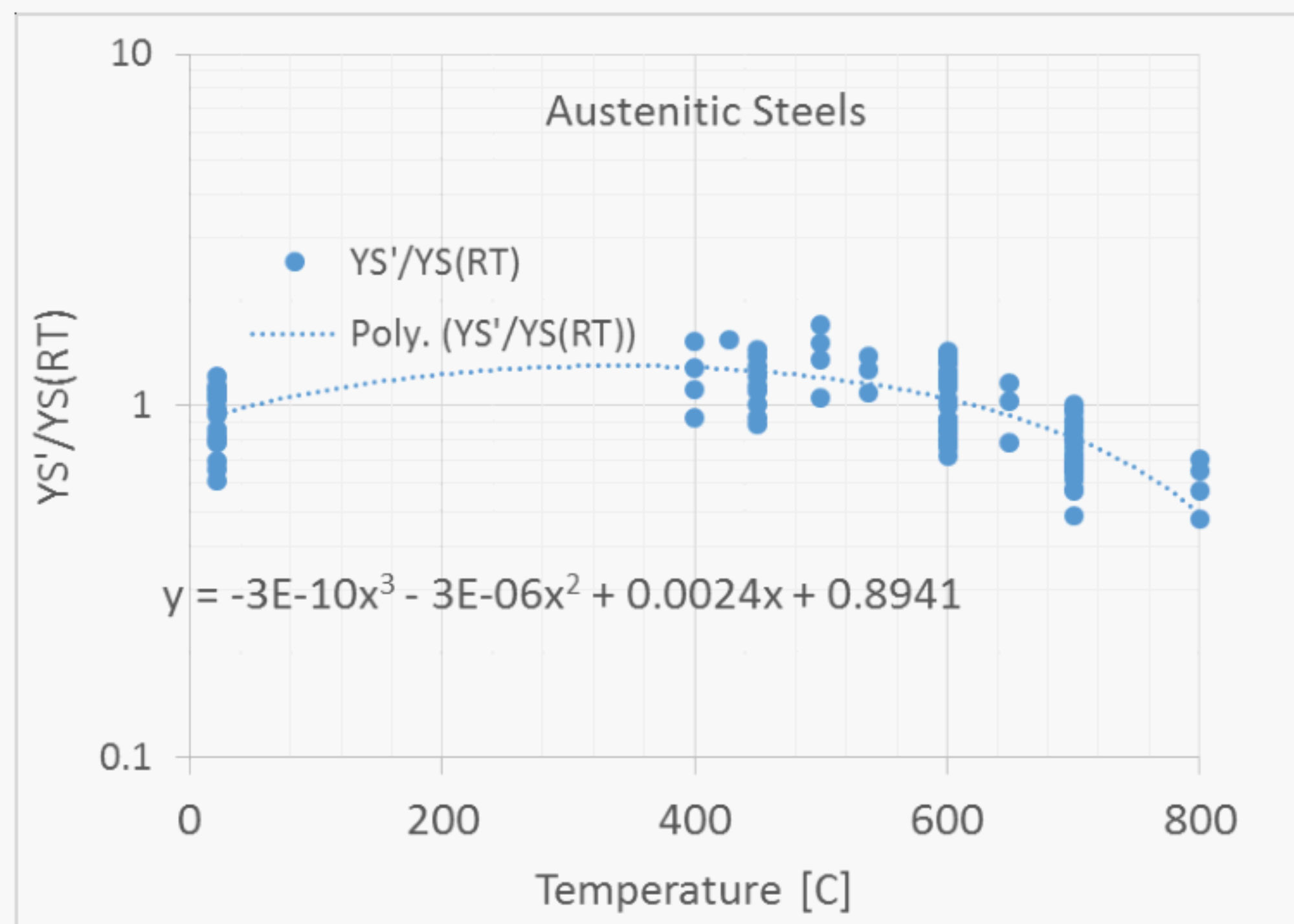


Figure 7-2: Ratio between cyclic yield stress (YS') and monotonic yield stress at room temperature ($YS(RT)$) as a function of temperature for austenitic steels



The material tends strongly toward cyclic hardening. For high yield stresses, cyclic softening can also occur. This seems to be mainly the case for cold-hardened qualities [7], [8]. At room temperature, huge differences

were reported between cyclic stress-strain curves determined by companion sample tests and by incremental step tests [9]. Formation of deformation-induced martensite was found to be dependent upon the type of test leading to such substantial differences. A different approach for the assessment of the cyclic response was tried for austenitic steels. According to the literature [10], almost no difference between cyclic stress-strain curves at room temperature and at 500 C was found. Therefore, correlations between cyclic properties and temperature were tried. The best results were obtained when the ratio between cyclic yield strength at temperature and yield strength at room temperature was used (Figure 7-2).

$$YS'/YS(RT) = c_1*T^3 + c_2*T^2 + c_3*T + c_4$$

Where:

$$c_1 = -3.48E-10$$

$$c_2 = -3.30E-06$$

$$c_3 = 2.36E-03$$

$$c_4 = 8.94E-01$$

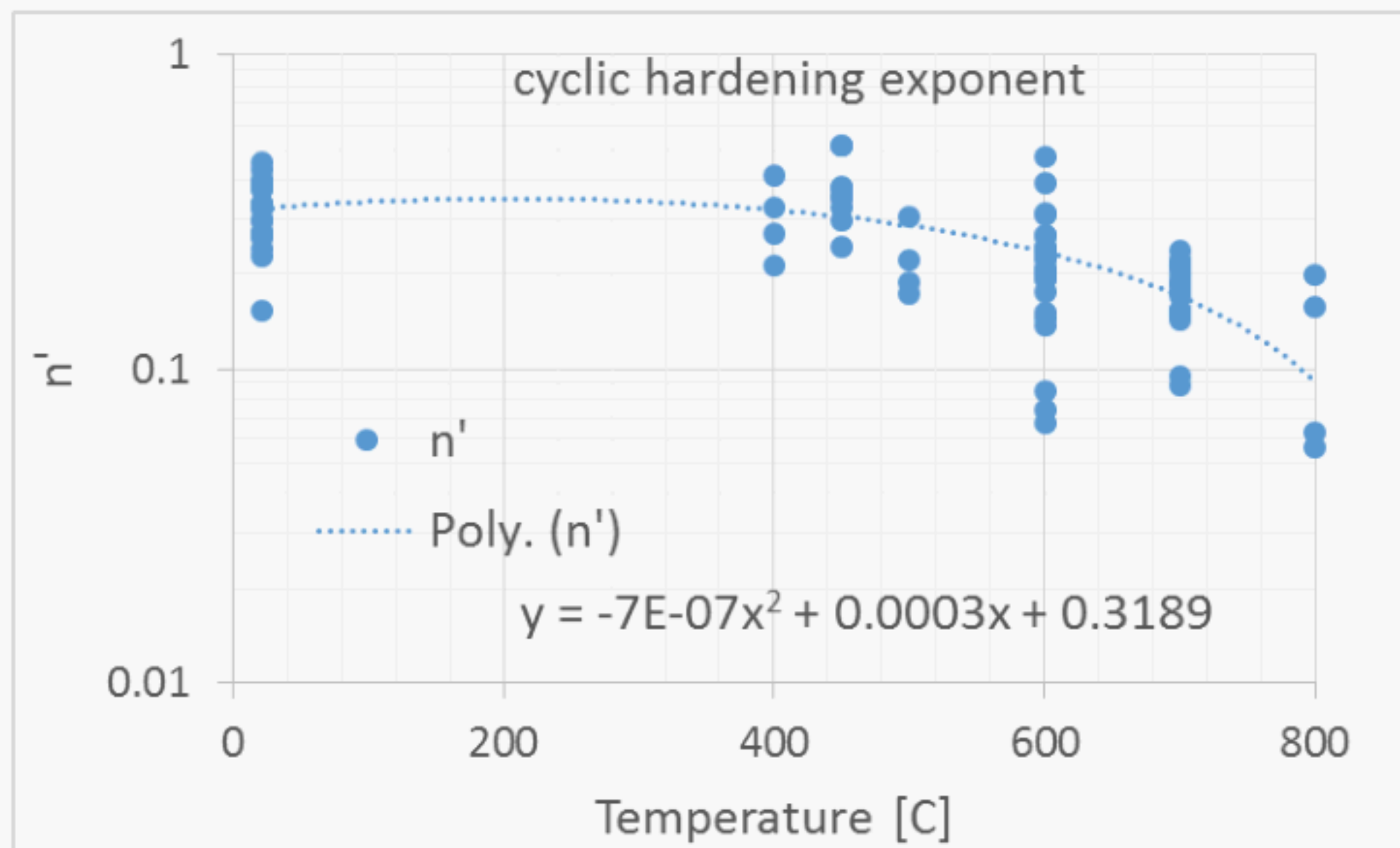
YS'=cyclic yield strength at temperature

YS(RT)=yield strength at room temperature

Temperature in degrees Celsius

For the cyclic hardening exponent, a similar temperature dependence was found, and is illustrated in Figure 7-3.

Figure 7-3: Cyclic hardening exponent, n' , as a function of temperature for austenitic steels



The relationship between cyclic hardening exponent n' and the temperature can best be described with a second order polynomial:

$$n' = d_1*T^2 + d_2*T + d_3$$

Where:

$$d_1 = -7.32E-07$$

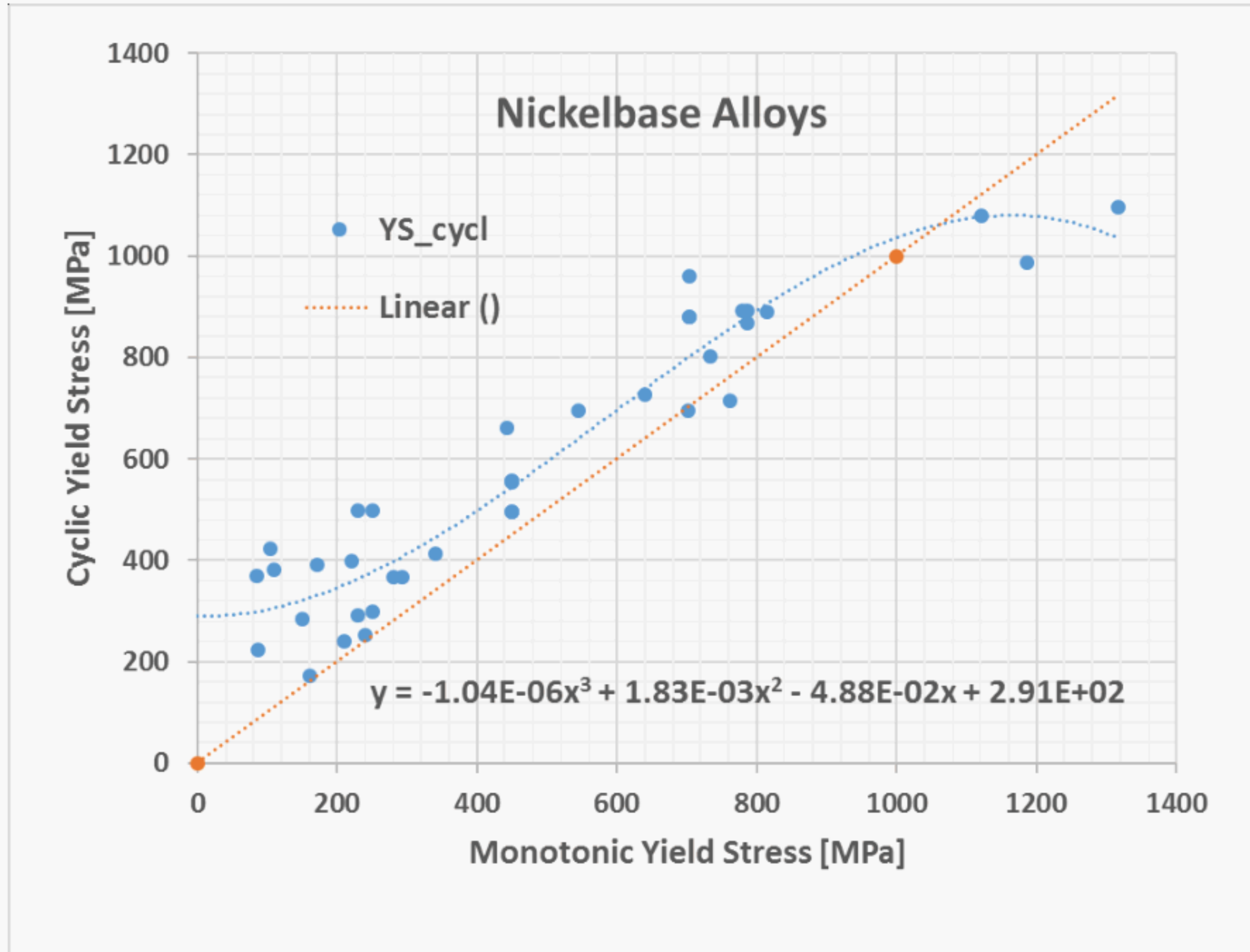
$$d_2 = 3.00E-04$$

$$d_3 = 3.19E-01$$

8 NICKEL-BASE ALLOYS

For nickel-base alloys, a relationship between monotonic and cyclic yield stress could be established as shown in Figure 8-1.

Figure 8-1: Relationship between monotonic and cyclic yield stress for nickel-base alloys



Except for very high yield strengths, a tendency for cyclic hardening was found. The data could best be fitted with a third order polynomial through 0/0:

$$YS' = e_1 * YS^3 + e_2 * YS^2 + e_3 * YS + e_4$$

Where:

$$e_1 = -1.04E-06$$

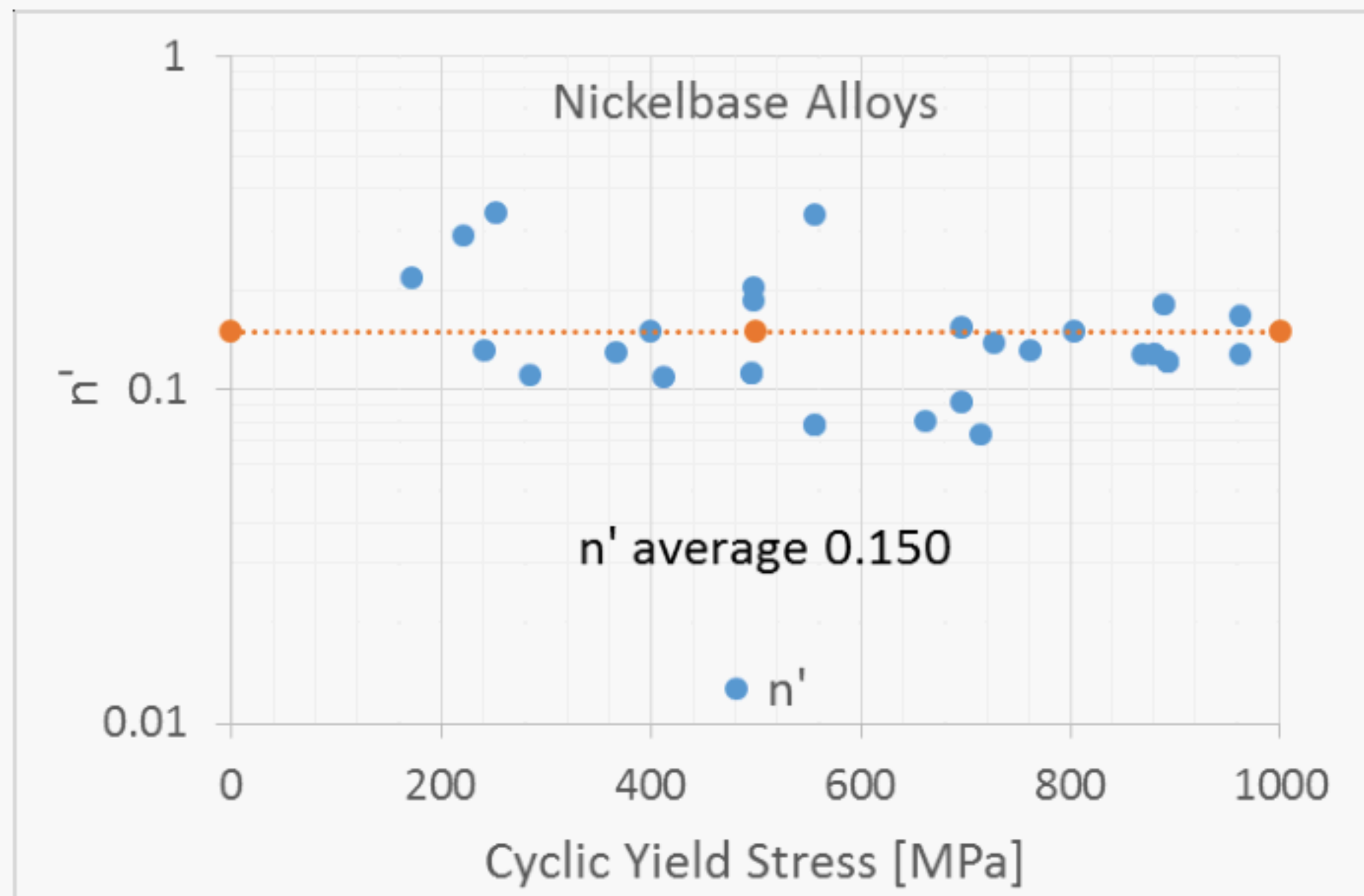
$$e_2 = 0.00183$$

$$e_3 = -0.0488$$

$$e_4 = 291$$

An average cyclic hardening exponent of 0.150 could be determined as shown in Figure 8-2.

Figure 8-2: Average cyclic hardening exponent for nickel-base alloys

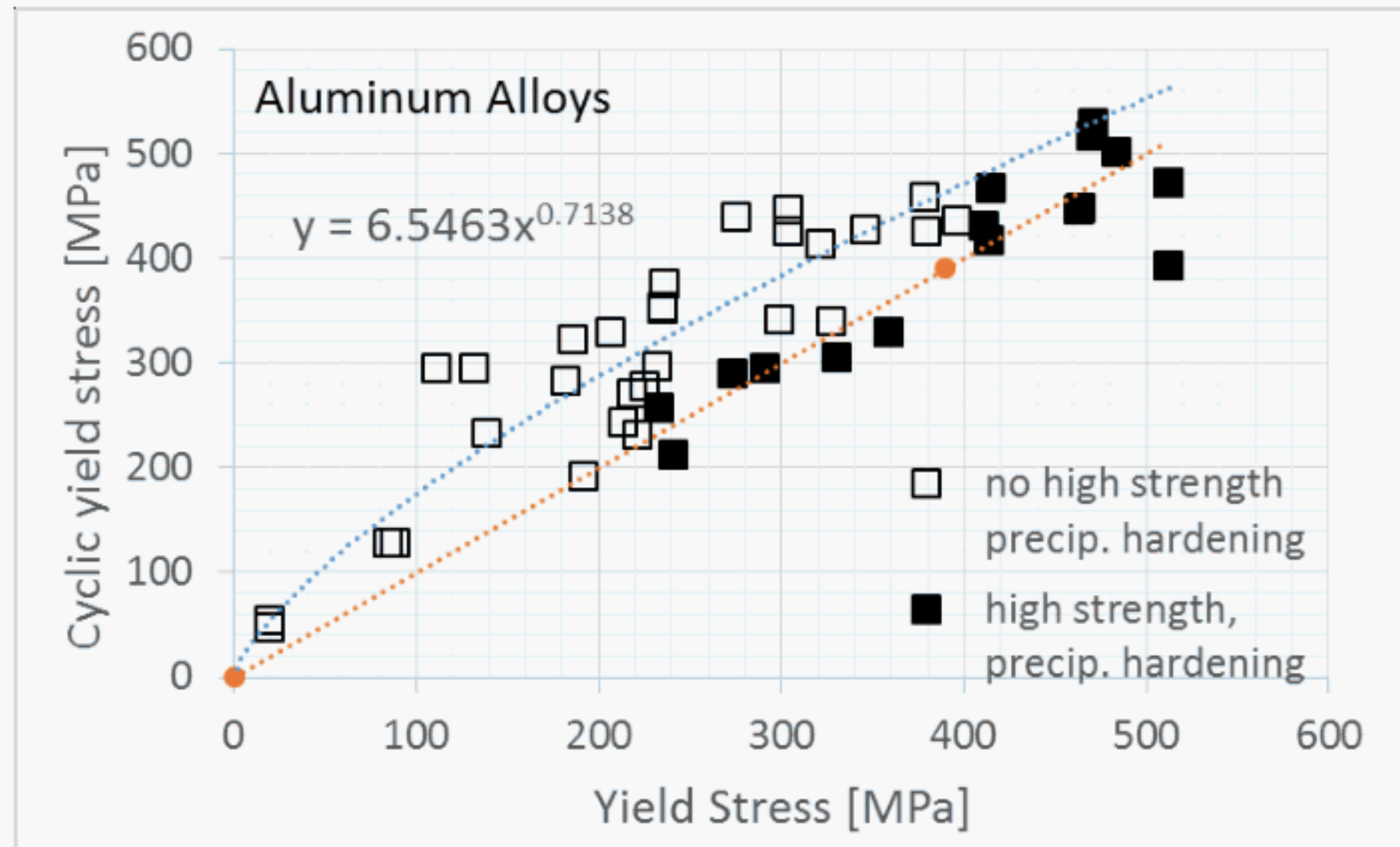


Based on the results shown in Figure 8-1, it can be concluded that nickel-base alloys tend to cyclic hardening up to monotonic yield strength values of about 1000 MPa. The monotonic stress-strain curves can be considered as conservative assessments of the cyclic behavior. The average values of YS' and n' can be used for a non-conservative general assessment of the cyclic materials properties.

9 ALUMINUM ALLOYS

The relationship between monotonic and cyclic yield stress for different aluminum alloys is shown in Figure 9-1. The precipitation-hardened high strength grades appear to remain cyclically stable whereas the other aluminum alloys tend to cyclic hardening.

Figure 9-1: Cyclic yield strength as a function of monotonic yield strength for aluminum alloys



The hardening curve could be best approximated by a power law fit.

$$YS' = f_1 * YS^{f_2}$$

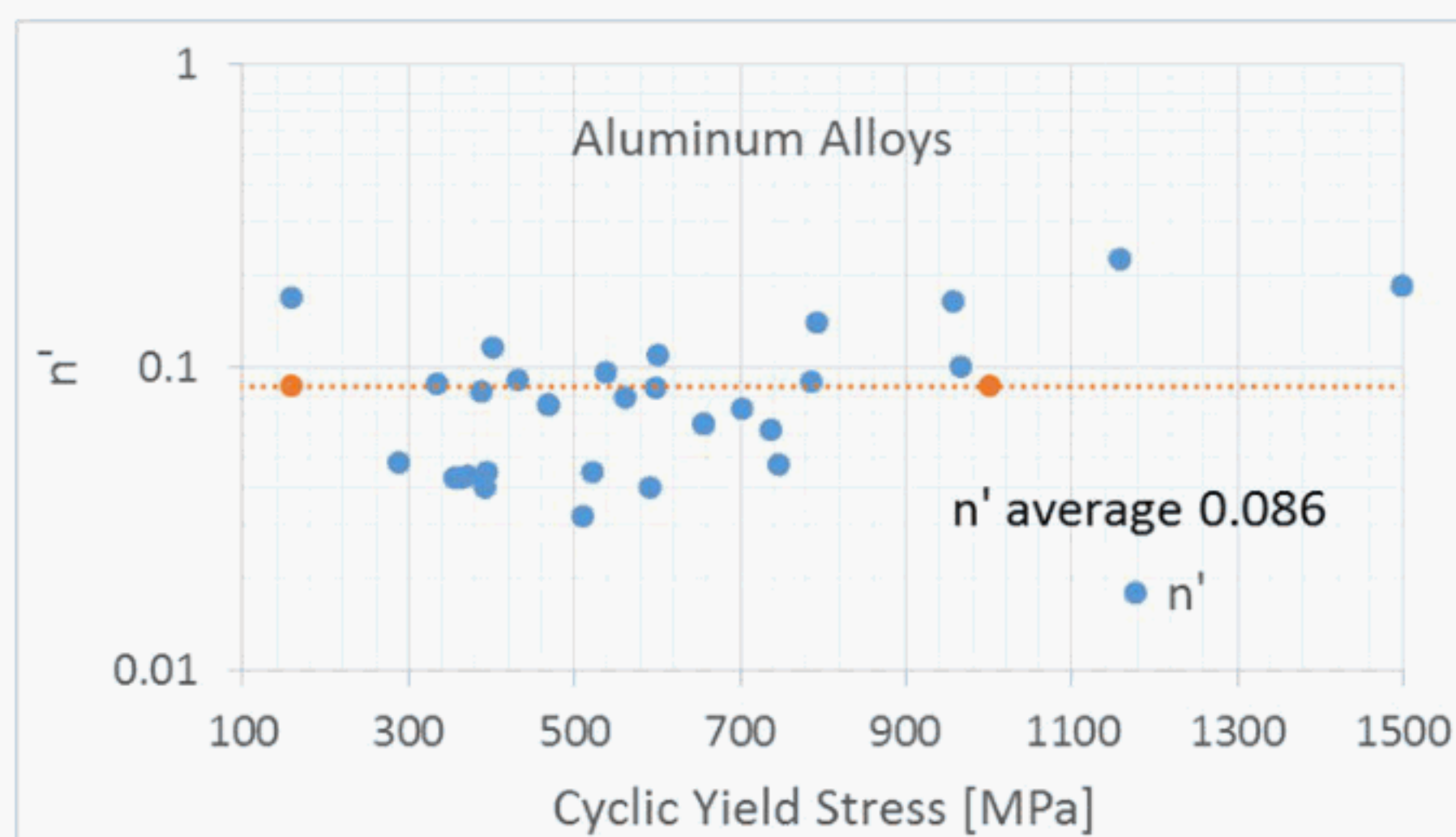
Where:

$$f_1 = 6.5463$$

$$f_2 = 0.7138$$

The average cyclic hardening exponent, n' , was determined to be 0.086 and is illustrated in Figure 9-2.

Figure 9-2: Average cyclic hardening exponent for aluminum alloys



Although aluminum alloys tend basically to cyclic hardening, it is proposed to use the monotonic curve for safety-relevant cyclic assessments because of the fact that the precipitation-hardening alloys particularly in the T4-T6 temper conditions don't show cyclic hardening. This behavior can also be found at elevated temperatures as shown for aluminum alloy A 6061 in Figure 9-3 and Figure 9-4.

Figure 9-3: Monotonic and cyclic stress-strain curves for aluminum alloy A 6061 at 100 C [11]

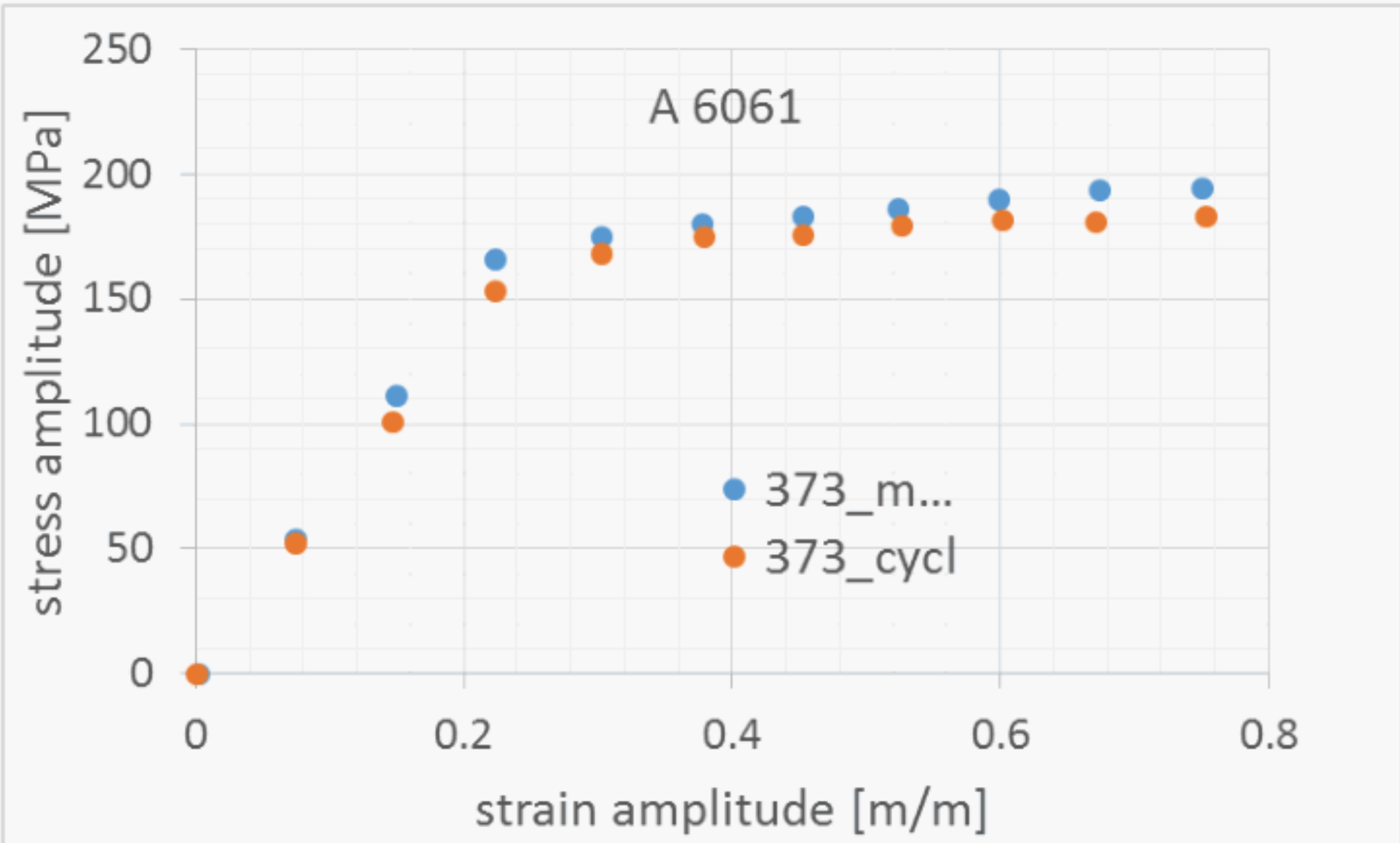
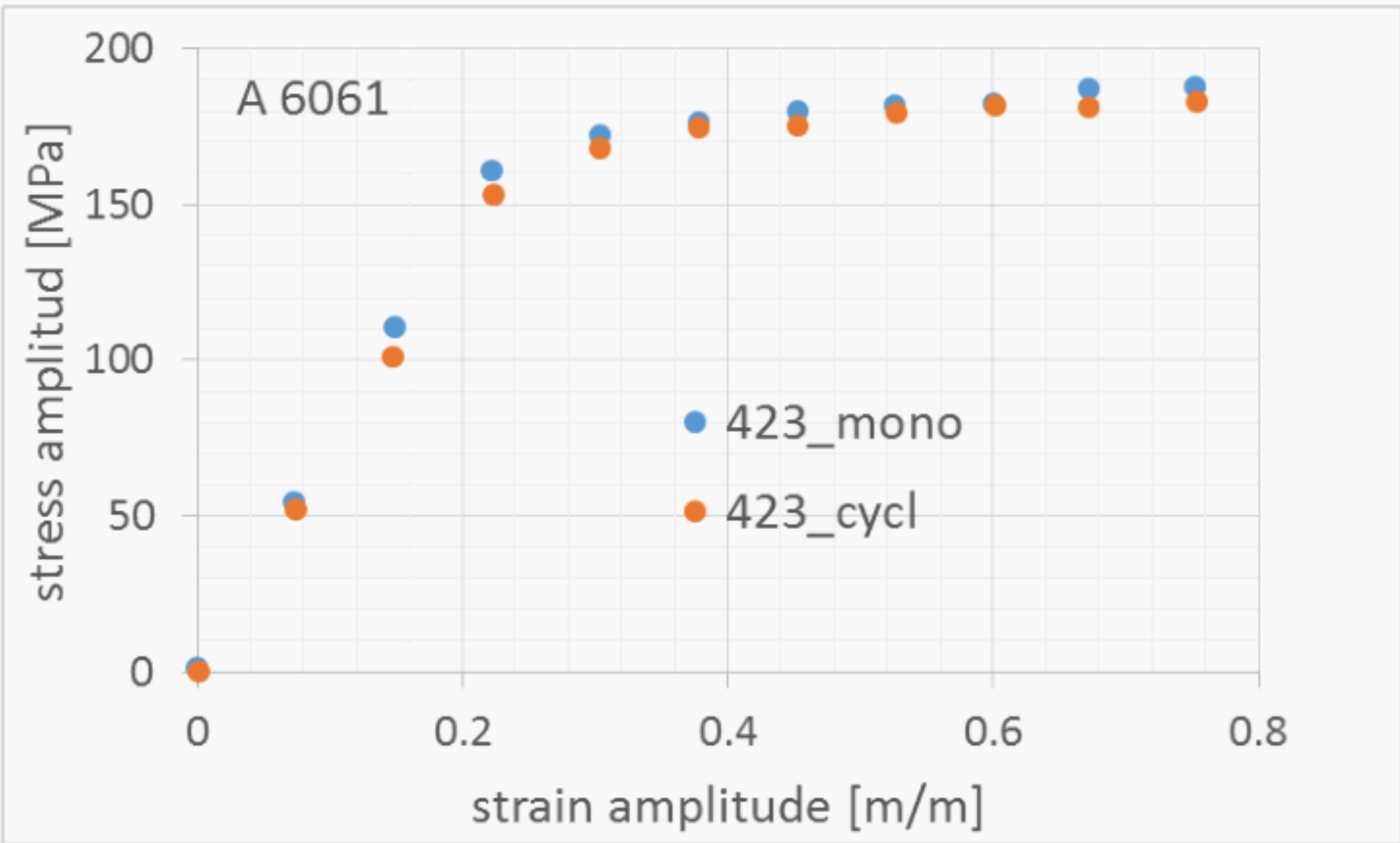


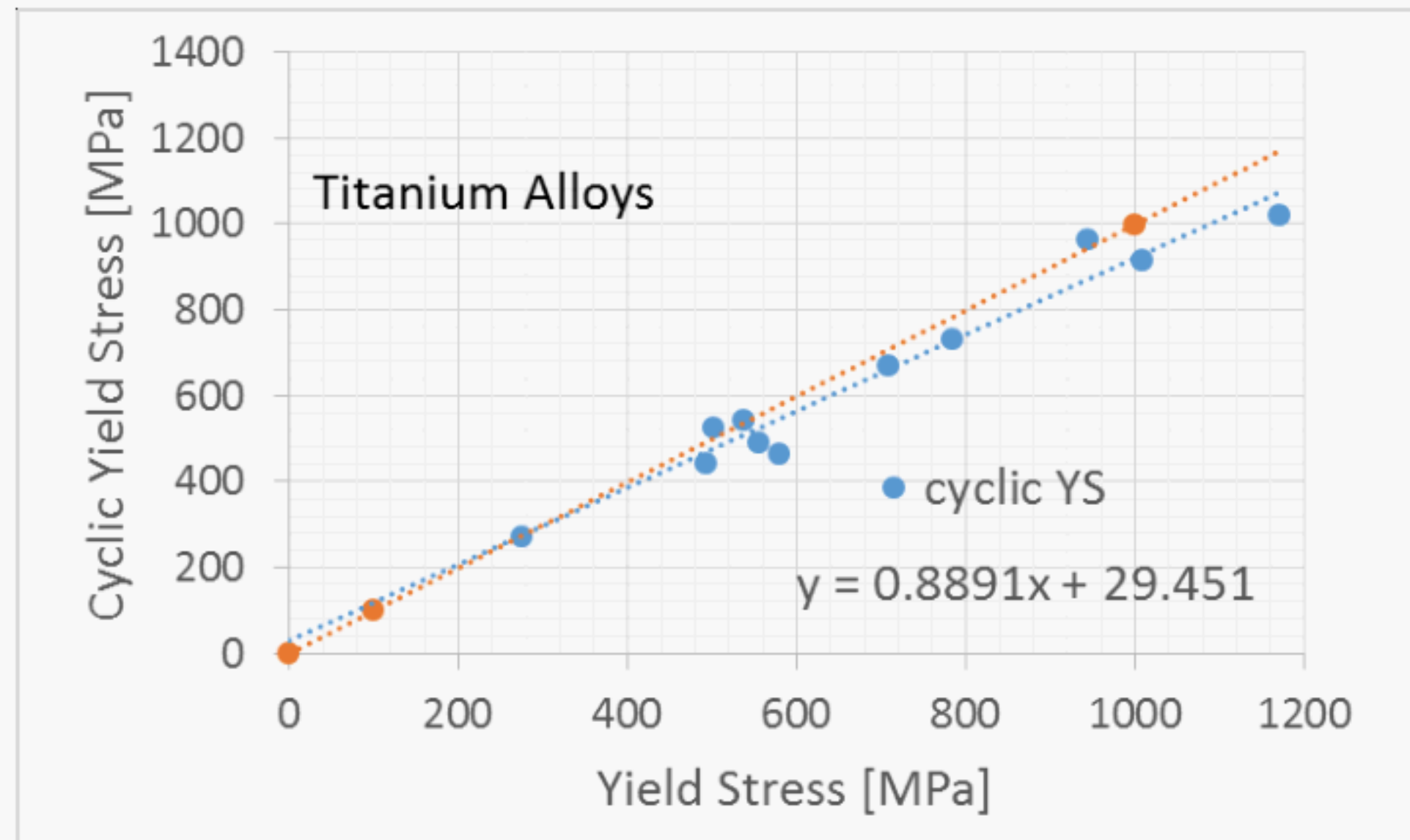
Figure 9-4: Monotonic and cyclic stress-strain curves for aluminum alloy A 6061 at 150 C [11]



10 TITANIUM ALLOYS

For titanium alloys, only a limited set of data was available for assessment of the cyclic behavior (Figure 10-1 and Figure 10-2).

Figure 10-1: Cyclic yield stress as a function of monotonic yield stress for titanium alloys

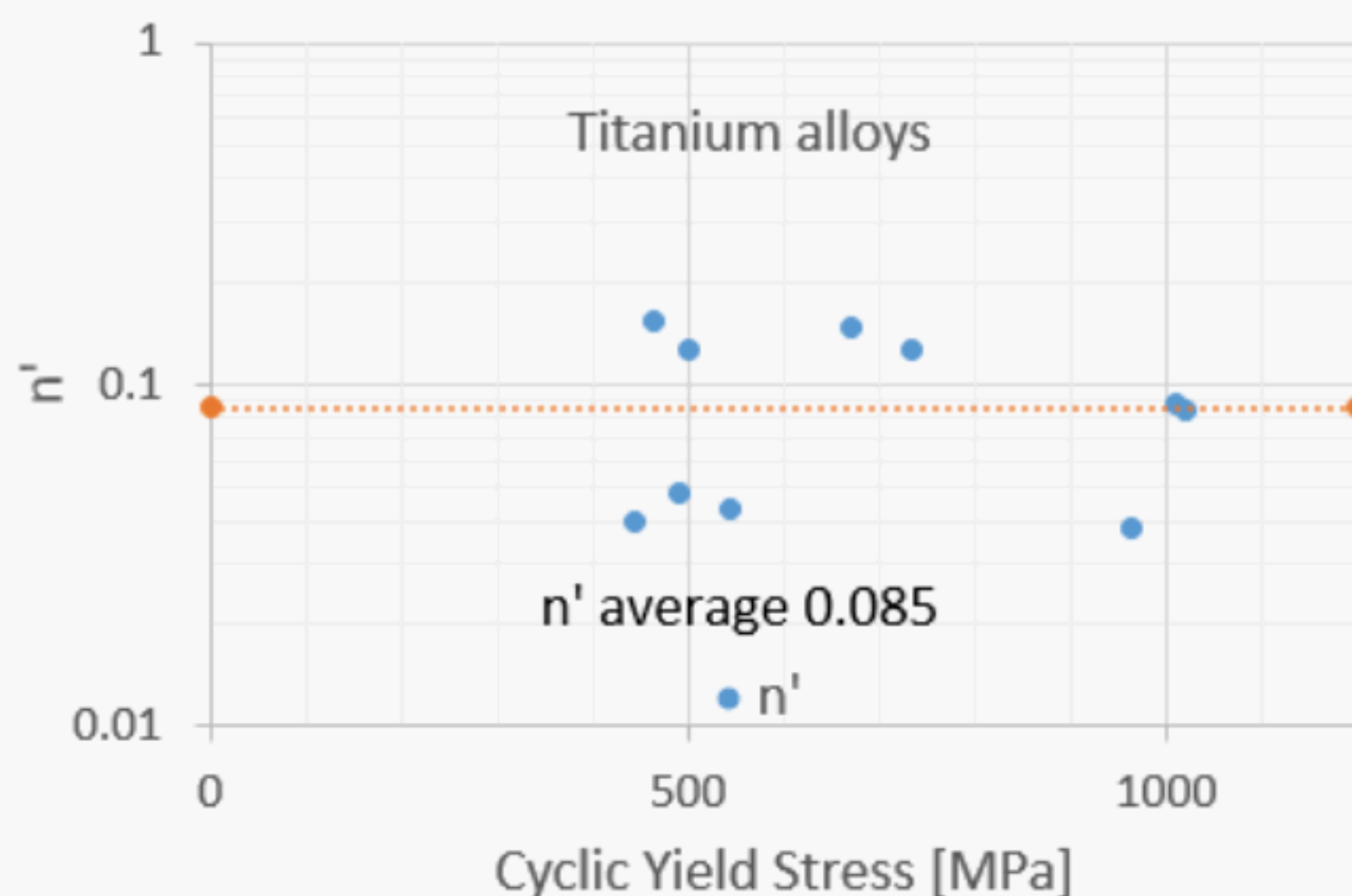


Titanium alloys tend to cyclic softening. The relationship between monotonic and cyclic yield stress can be written as a linear function and is illustrated in Figure 10-1.

$$YS' = 0.8891 * YS + 29.451$$

The average cyclic hardening exponent is 0.085 and is illustrated in Figure 10-2.

Figure 10-2: Average cyclic hardening exponent for titanium alloys



11 COPPER AND ZIRCONIUM ALLOYS

For copper and zirconium alloys, no data for a serious assessment of their cyclic behavior could be found.

In general, it can be stated that copper (in an annealed or soft condition) has a trend toward cyclic hardening similar to other face-centered material like aluminum or nickel. After cold deformation, copper might tend to cyclic softening.

Zirconium has a hexagonal lattice and it is expected to exhibit behavior similar to titanium. This expectation could be verified for Zircaloy, however the data do not allow for a more general assessment.

12 DETERMINATION OF CYCLIC AND MONOTONIC STRESS-STRAIN CURVES FROM GIVEN YS AND UTS-VALUES

It is the aim of this report to provide a basis for determination of cyclic and monotonic stress-strain curves using only yield strength and ultimate tensile strength as given in Tables IID (Y-1, U). Based on the considerations described in the previous sections, an Excel worksheet was created which allows the production of monotonic and cyclic stress-strain curves from YS, UTS, E, and Temperature. A description of the Excel worksheet is given in Appendix A:.

13 IMPLEMENTATION INTO THE ASME MATERIALS DATABASE

Although currently no fatigue-related data in the ASME Materials Database exists, an implementation of the results could be envisaged.

In many summaries of cyclic data, a scheme similar to the one shown in Figure 13-1 is used.

Figure 13-1: Scheme for presentation of cyclic and monotonic data

Mat	Temp	E	YS-monot	UTS-monot	YS-cyclic	K'	n'	K	n
-----	------	---	----------	-----------	-----------	----	----	---	---

The designations are as follows:

- Mat=Material
- Temp=Temperature
- E=Young's Modulus
- YS-monot=Monotonic Yield Stress
- UTS-monot=Monotonic Ultimate Tensile Stress
- YS-cyclic=Cyclic Yield Stress
- K'=Coefficient of cyclic curve
- n'=Exponent of cyclic curve
- K=Coefficient of monotonic curve
- n=Exponent of monotonic curve

Such a representation is given in the National Institute for Materials Science (NIMS) database for cyclic curves. It is also used in a database of the German University of Darmstadt:

http://www.werkstoffmechanik.tu-darmstadt.de/materials_database/index.de.jsp

The NIMS database is already included in the ASME Materials Database and therefore no specific measures are needed. The University of Darmstadt fatigue database allows public access via user/password given on the database page (see link above).

Those two databases go even further to Coffin-Manson representations of the S/N curves, which might be a next step also for ASME's purpose.

Although this appears to be a very condensed representation of cyclic stress-strain data, it says more than isolated points which can of course also be included. Appendix B: lists almost 300 such entries which were created during the preparation of this report. The table is not complete and although additional information still exists, it cannot be fully completed because not all information is available, however, the data shown were sufficient to prepare the spreadsheets. Such input could be considered as a starting point to later implementing cyclic stress-strain data into the ASME Materials Database. In the preparation of this report, more than 100 related papers were collected and reviewed.

14 CONCLUSIONS AND OUTLOOK

The main results of this report are discussed at length in the “Summary” section.

The cyclic response (cyclic stress-strain curves) of different classes of materials were investigated based upon the available literature. The hysteresis loop at $N_f/2$ was taken as reference. The scatter of material data, limited data and complex (non-standardized) testing conditions allow only assessments of the average cyclic material behavior.

The proposed procedure requires only the yield stress, ultimate tensile stress and Young’s modulus of a given material. It can therefore be performed for materials given in ASME BPVC Section II Tables IID.

The cyclic data can be obtained from an Excel worksheet which allows for the calculation of monotonic stress-strain curves and cyclic stress-strain curves. The results are available as Figures and Tables. Engineering and true stress-strain curves can be reported.

A possibility for implementation of the results into the ASME Materials Database is discussed. Based on the literature collected, it could be possible to extend the assessment to Coffin-Manson plots of fatigue curves.

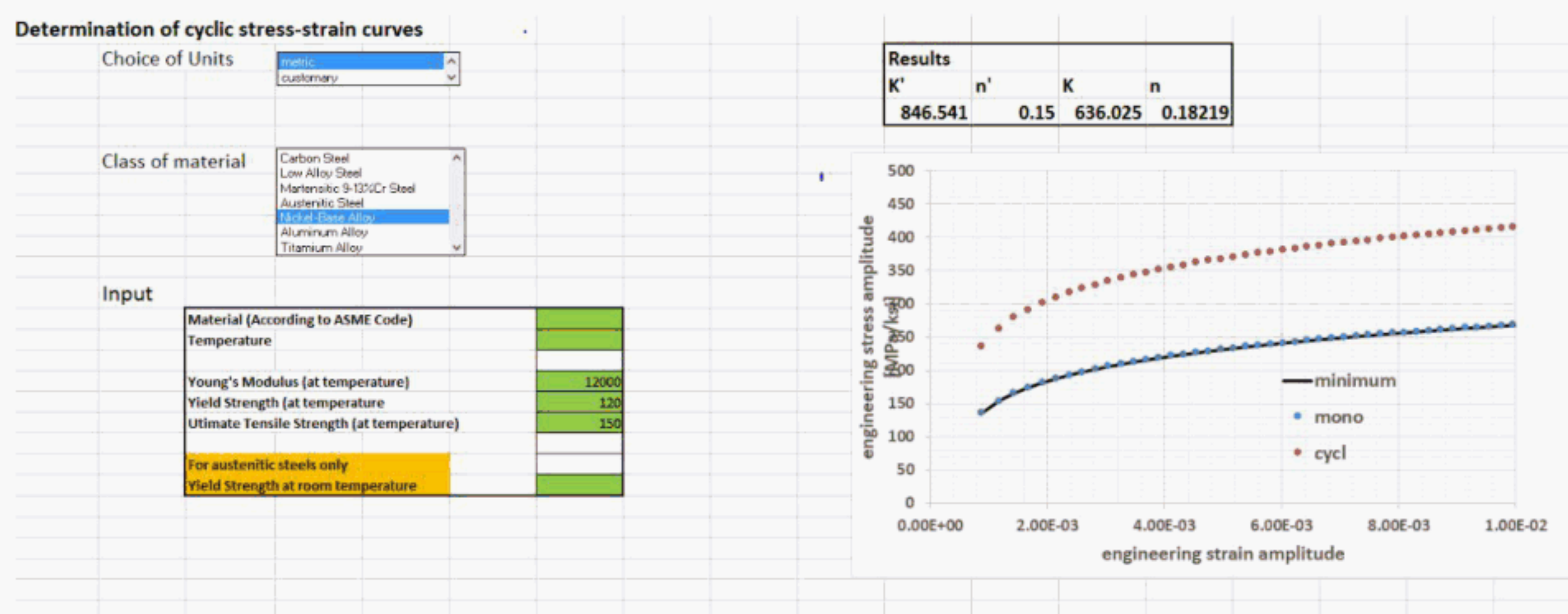
APPENDIX A: EXCEL WORKSHEET FOR DETERMINATION OF CYCLIC STRESS-STRAIN CURVES

The worksheet allows for the determination of monotonic and cyclic curves from the following input parameters:

- Type of material
- Yield strength (Y-1)
- Ultimate Tensile Strength (U , eventually divided by 1.1 to get the real UT)
- Young's Modulus
- Temperature (mandatorily necessary only for austenitic stainless steels)
- Yield Strength at room temperature (Y-1) (mandatorily necessary only for austenitic stainless steels)
- Short Materials identification

A screenshot of the input sheet is shown in Figure A-1.

Figure A-1: Screenshot of the spreadsheet for determination of stress-strain curves



From the information given, the spreadsheet calculates the data necessary for determination of the cyclic curves using the different analyses shown in the previous progress report:

- K = coefficient of the power law for the monotonic curve
- n = exponent of the power law for the monotonic curve
- K' = coefficient of the power law for the cyclic curve
- n' = exponent of the power law for the cyclic curve

Figure A-1 is a printout of the Excel spreadsheet where the information is created.

APPENDIX B: CYCLIC STRESS- STRAIN DATA

Mat	T (C)	E	YS-monot	UTS-monot	YS-cycl	K'	n'	K	n
Carbon Steels									
A516Gr70	RT	204000	325	993	335	983	0.173		
Low Carbon	RT		225		286	723	0.149		
S25C_D	RT		346	507	321	816	0.15		
S25C_E	RT		307	464	307	756	0.145		
S25C_J	RT		366	527	345	860	0.147		
S35C_C_N	RT		396	565	346	976	0.167		
S35C_G_N	RT		394	593	367	985	0.159		
S35C_K_N	RT		414	617	363	1065	0.173		
S35C_K_QT	RT		587	780	450	1248	0.164		
S35C_C_QT_600	RT		480	656	392	1001	0.151		
S35C_G_QT_600	RT		596	733	454	1205	0.157		
S35C_K_QT_600	RT		542	730	457	1236	0.16		
Carbon 45	RT		450		384	1097	0.169		
S45C_B	RT		432	659	372	1030	0.164		
S45C_F	RT		466	737	388	1196	0.181		
S45C_I	RT		462	672	369	1102	0.176		
S45C_I_QT 550	RT		702	863	500	1411	0.167		
S45C_C_QT 600	RT		551	774	448	1151	0.152		
S45C_F_QT 600	RT		728	844	483	1424	0.174		
S45C_I_QT 600	RT		652	787	466	1290	0.164		
S45C_I_QT 650	RT		588	730	420	1163	0.164		
S49C	RT		306	524	308	1093	0.204		
S49C	200		277	447	311	958	0.181		
S49C	500		175	340	233	618	0.157		
			310		288	1117	0.218		
			312		289	1120	0.218		
			312		294	1198	0.226		
			213		402	948	0.138		
			208		420	827	0.109		
			213		409	976	0.14		
			200		421	1305	0.182		
			197		281	871	0.182		
			191		327	862	0.156		
			185		286	783	0.162		
	500		162		168	319	0.103		
	500		173		230	584	0.15		
	500		158		173	354	0.115		
	500		208		224	632	0.167		

Mat	T (C)	E	YS-monot	UTS-monot	YS-cycl	K'	n'	K	n
			385		328	955	0.172		
			400		313	1140	0.208		
			385		318	998	0.184		
			350		314	1116	0.204		
			400		319	952	0.176		
			385		309	815	0.156		
			340		318	679	0.122		
Low alloy steels									
SCr440_QT_550	RT		903	1006	682	1925	0.167		
SCr440_QT_600	RT		813	921	567	1523	0.159		
SCr440_QT_600	RT		845	952	570	1559	0.162		
SCr440_QT_600	RT		833	943	581	1589	0.162		
SCr440_QT_650	RT		717	840	517	1330	0.152		
SCM435_QT_550	RT		1017	1088	626	1767	0.167		
SCM435_QT_600	RT		847	939	546	1439	0.156		
SCM435_QT_600	RT		893	978	579	1625	0.166		
SCM435_QT_600	RT		980	1078	678	1722	0.15		
SCM435_QT_650	RT		780	881	522	1411	0.16		
SCMV_3	RT		393	556	369	893	0.142		
SCMV_3	300		282	532	402	730	0.096		
SCMV_3	400		266	522	410	542	0.045		
SCMV_3	500		244	438	345	567	0.08		
SCMV_3	600		188	294	208	515	0.146		
SCMV2_2NT_20	RT		318	481	321	660	0.116		
SCMV2_2NT_50	RT		317	494	332	638	0.105		
SCMV2_2NT_20	200		264	428	300	656	0.126		
SCMV2_2NT_50	200		263	435	284	648	0.133		
SCMV2_2NT_20	300		233	447	347	623	0.094		
SCMV2_2NT_50	300		236	447	358	607	0.085		
SCMV2_2NT_20	400		216	436	365	626	0.087		
SCMV2_2NT_50	400		222	445	353	577	0.079		
SCMV_4	RT		532	684	428	796	0.1		
SCMV_4	300		466	591	376	741	0.109		
SCMV_4	400		474	575	402	730	0.096		
SCMV_4	500		388	498	340	652	0.105		
SCMV_4	600		313	404	257	428	0.082		
A470_8	RT		605	773	464	1028	0.128		
A470_8	400		516	659	412	912	0.128		
A470_8	500		480	561	335	815	0.143		

STP-PT-081: Cyclic Stress-Strain Curves

Mat	T (C)	E	YS-monot	UTS-monot	YS-cycl	K'	n'	K	n
A470_8	550		430	488	303	693	0.133		
A470_8	600		355	422	215	556	0.153		
			218		242	740	0.18		
			218		214	700	0.191		
			295		260	598	0.134		
			405		346	941	0.161		
			340		338	948	0.166		
			320		323	830	0.152		
Martensitic Steels									
Grade 91	RT	215000	531	682	471	975	0.117		
Grade 91	500	180000	396	477	305	693	0.132		
Grade 91	550	172000	346	417	252	609	0.142		
Grade 91	600	158000	255	230	209	443	0.121		
Grade 91	650	140000	173	277	158	343	0.125		
SUH.616B_NIMS	RT	216000	894	1090	745	1600	0.123		
SUH.616B_NIMS	300	194000	766	922	655	1390	0.121		
SUH.616B_NIMS	400	117000	723	882	625	1350	0.124		
SUH.616B_NIMS	500	179000	597	740	528	1060	0.112		
SUH.616B_NIMS	600	157000	388	528	350	660	0.102		
X20CrMo12 1	RT	210000	795	1013	730	1301	0.093		
	400	191800	647	816	589	1096	0.1		
	400	191800	647	816	613	1034	0.084		
	500	185850	538	700	507	1151	0.132		
	500	185850	538	700	465	910	0.108		
	600	166950	350	492	384	895	0.136		
	600	166950	350	492	280	355	0.038		
	rt	210000	795	1013	716	1325	0.099		
Austenitic Steels									
SUS 310-B	21	210000	271		289	2302	0.334		
	21	210000	271	630	284	2242	0.332		
	450	165650	178	521	273	1754	0.299		
	450	165650	178	521	353	1627	0.246		
	600	163550	161	456	304	1404	0.246		
	600	163550	161	456	341	1026	0.177		
	700	164000	156	357	179	617	0.199		
	700	164000	156	357	242	700	0.171		
SUS 304-B	21	210000	207	611	202	3001	0.434		
	450	170500	106	435	184	4497	0.514		

STP-PT-081: Cyclic Stress-Strain Curves

Mat	T (C)	E	YS-monot	UTS-monot	YS-cycl	K'	n'	K	n
	450	170500	106	435	229	2363	0.375		
	600	158000	92	373	217	1544	0.316		
	21	210000	207	611	196	3330	0.455		
	600	158000	92	373	238	1031	0.236		
	600	158000	92	373	276	437	0.074		
	700	152000	81	278	189	473	0.147		
	700	152000	81	278	157	587	0.212		
	700	152000	81	192	142	372	0.154		
	800	160000	73	192	136	365	0.159		
	800	160000	73	192	99	146	0.063		
SUS 304-HP	21	198000	242	666	275	2872	0.378		
	400	173000	156	445	224	2917	0.413		
	500	163000	162	422	254	1684	0.304		
	600	154000	146	360	219	1162	0.268		
	600	154000	136	360	221	996	0.242		
	600	154000	146	360	242	411	0.085		
	600	154000	146	360	195	497	0.151		
	700	143000	128	252	177	575	0.19		
	700	143000	128	252	164	532	0.189		
	700	143000	128	252	140	253	0.095		
	700	143000	128	252	118	204	0.089		
	600	154000	146	360	213	1106	0.265		
	600	154000	146	360	205	727	0.204		
	700	143000	128	252	167	432	0.153		
	700	143000	128	252	159	390	0.144		
	600	154000	146	360	194	853	0.238		
	600	154000	146	360	188	624	0.193		
	700	143000	128	252	156	406	0.154		
	700	143000	128	252	139	433	0.183		
316-HP	21	210000	257	606	313	2000	0.298		
	400	171500	184	513	287	2204	0.328		
	400	171500	184	513	331	1789	0.271		
	400	171500	184	513	394	1504	0.215		
	500	178000	178	493	348	1406	0.224		
	500	178000	178	493	389	1155	0.175		
	500	178000	178	493	436	1409	0.189		
	600	168500	164	449	308	1230	0.223		
	600	168500	164	449	306	1262	0.228		
	600	168500	164	449	652	991	0.067		
	700	175000	155	319	207	818	0.221		

Mat	T (C)	E	YS-monot	UTS-monot	YS-cycl	K'	n'	K	n
	700	175500	155	319	183	550	0.177		
	700	175500	155	319	159	395	0.147		
X 5 CrNiMo 18 10	21	210000	231	587	247	2755	0.388		
	21	210000	230	587	256	1644	0.299		
	450	170000	128	465	213	5290	0.516		
	450	170000	128	465	282	2994	0.38		
	450	170000	128	465	321	2909	0.354		
	600	167000	114	405	306	1104	0.206		
	600	167000	114	405	317	1063	0.194		
	600	167000	114	405	322	799	0.146		
	700	159000	113	313	227	859	0.213		
	700	159000	113	313	223	573	0.152		
	700	159000	113	313	196	728	0.211		
	800	123600			163	567	0.2		
	800	123600			132	187	0.056		
	21	210000	228	650	258	2674	0.376		
	21	210000	228	665	258	2081	0.336		
	450	135300	145	529	262	2292	0.349		
	450	135300	145	529	335	2541	0.326		
	600	170000	135	481	286	1995	0.312		
	600	170000	135	481	327	1147	0.202		
	700	168000	114	326	233	936	0.223		
	700	168000	114	326	201	893	0.24		
	700	168000	114	326	184	471	0.151		
304	21	186200			316	1424	0.242		
	21	186200			323	1672	0.265		
	21	186200			281	3200	0.392		
316 L	21	220000	273	572	246	1977	0.335		
	21	240000	375	712	298	1598	0.27		
	21	220000	294	600	229	2827	0.404		
	21	240000	400	746	306	1566	0.263		
	21	220000	306	619	260	1946	0.324		
	21	240000	404	756	321	1746	0.273		
	600	80000	156	431	343	1228	0.205		
	600	80000	183	433	315	1155	0.209		
	600	168000	242	539	285	3302	0.394		
	600	168000	306	542	270	5223	0.477		
Superalloys									
gamma'-A	21		701	1021	696	1233	0.092		

Mat	T (C)	E	YS-monot	UTS-monot	YS-cycl	K'	n'	K	n
gamma'-B	21		761	1097	715	1132	0.074		
GH4049	850		733	850	803	2040	0.15		
HastX	21		443		661	1095	0.081 2		
IN-690	21								
IN 690	21	196000	210	716	400				
Hast X	760	161000	220		400	1022	0.151		
HastX/617	538		230		498	1769	0.204		
HastX/617	871		150		285	569	0.111		
GH3044	600		250		498	1582	0.186		
IN617	760		280		366	817	0.129		
	760		210		241	544	0.131		
HA-230	760		340		413	818	0.11		
	760		160		173	670	0.218		
Inconel X	21		703		880	1950	0.128		
	21	214055	704	1215	961	2130	0.128		
	21	213800	703	1214	880	1950	0.128		
800H	21	210000	240	550	252	2070	0.339		
713	21	208800	787	932	893	1895	0.121		
713	21	208500	780	1001	893	1895	0.121		
IN 738	900	155000	449	509	557	4437	0.334		
	900	130000	449		496	994	0.112		
	900	130000	449		556	908	0.079		
	900	130000	449		496	995	0.112		
	900	130000	449		556	909	0.079		
Waspaloy A	21	210000	545		696	1814	0.154		
	21	210000	787	1091	869	1931	0.128		
	21	210000	815		889	2725	0.18		
TM-185	900	176000	640		728	1729	0.139		
IN-718	21		1316		1097				
IN-718	550		1186		988				
Re ⁹⁵ PM/average	649		1121		1080				
IN617	760		294		366				
IN 800	21		250		298				
IN800 HT	21		230		292				
			172		392		0.099		
			110		383		0.12		
			103		423		0.098		
			84		369		0.087		

STP-PT-081: Cyclic Stress-Strain Curves

Mat	T (C)	E	YS-monot	UTS-monot	YS-cycl	K'	n'	K	n
			86		224		0.101		
Aluminum									
2024-T351	RT	70300	303	476	448	786	0.09		
2024-T4_T	RT	73000	379	469	427	655	0.065		
2024-T4_C	RT	73000	303	634	427	655	0.065		
2024-T351	RT	72400	327	470	341	957	0.166		
2024-T3		74500	378	486	459	590	0.04		
356 cast	RT		213		245	432	0.091		
356 cast	RT		221		232	388	0.0827		
356 cast			191		193	335	0.088		
A 356 T6	RT	65000	181	268	283	372	0.044		
A 356 T6	RT	71000	231	276	297	393	0.045		
		70000	224	267	279	365	0.043		
		71000	218	255	272	355	0.043		
5086 F	RT	70000	206	310	331	600	0.11		
5182- 0 L	RT	72400	110	303	296	468	0.075		
5182-0 T	RT	72400	131	338	296	468	0.075		
5454-0	RT	69000	138	248	234	400	0.116		
5456-H331	RT	69000	234	400	352	599	0.086		
2014 -T6	RT	73000	462	510	448	703	0.073		
2014-T6	RT	74500	483	538	503	738	0.062		
2219-T851	RT	71000	358	469	331	793	0.14		
6061 T651	RT	69000	290	310	296	538	0.096		
7075-T6	RT	71000	469	579	517	965	0.1		
7075-T73	RT	71700	413	483	418	510	0.032		
6082-T6	RT	70000	330		306	392	0.04		
6060-T6	RT	70000	240		213	288	0.0484		
7075 T6		70940	512	572	473	1499	0.186		
7075 - T6		72230	512	572	394	521	0.045		
7475 T761		70010	414	475	468	675	0.059		
AlMg 4.5Mn		71500	298	363	342	562	0.08		
5083-H112	21	69000	185		324	591	0.097		
5456-H311	21	69050	235	400	376	636	0.084		
5456-H311	21	69000	234	400	355	600	0.084		
6061-T6		70000	232		258	445	0.088		
6351-T6	21	70000	273		290	460	0.074		
7005-T5	21	73000	410		432	791	0.097		
7075 - T6	21	70940	512	572	473	1499	0.186		

STP-PT-081: Cyclic Stress-Strain Curves

Mat	T (C)	E	YS-monot	UTS-monot	YS-cycl	K'	n'	K	n
7075 - T6	21	71120	470	580	530	913	0.088		
Al 2024-FC(B	21	71600	84		129	253	0.109		
Al 99.5	21	70000	19	73	55	453	0.337		
Al 99.5	21	70000	19	73	49	254	0.265		
2014-T6	21	69050	463	511	449	704	0.072		
AlCuMg-1	21	72060	321		414	1779	0.234		
AlCuMg-2	21	73300	396	490	436	557	0.039		
2024-T3	21	82000	378	486	459	590	0.04		
2024-T3	21	74500	378	486	599	4206	0.314		
AlCuMg-2	21	70280	345	490	428	843	0.109		
AlCuMg-2	21	74600	88	245	129	453	0.201		
AlCuMg-2	21	74100	275	446	440	648	0.062		
Titanium									
TiAlSn	350		494		445	570	0.039 8	682	0.052
	350		555		492	665	0.048 6	1041	0.101
Ti 6 4	350		536		544	711	0.043 1	663	0.034
IMI 834	21		945	1060	963	1219	0.038		
	600		580	670	464	1201	0.153		
exp	21		1170		1020	1727	0.084 8	1588	0.049
	300		784		732	1610	0.126 8	1652	0.120
	500		709		671	1684	0.148	1725	0.143
Ti	21	120000	275	520	274	7383	0.53		
Ti 829	21	111000	1010		916	1583	0.088		
	600	122000	503		526	1303	0.146	1350	0.159

APPENDIX C: PROBLEMS WITH NON-CORRELATED MONOTONIC AND CYCLIC STRESS-STRAIN CURVES TAKING GRADE 91 AS AN EXAMPLE

ASME BPVC Section VIII/2 mentions cyclic stress-strain curves of 9Cr-1Mo steel (see Figure C-1):

Figure C-1: Cyclic curve for 9Cr-1Mo in Section VIII/2 showing temperature (C), n' and K'

9Cr-1Mo	20	0.117	975
	500	0.132	693
	550	0.142	609
	600	0.121	443
	650	0.125	343

Comparison with NIMS data for Grade 91 (see Figure C-2) clearly shows that these data were copied from the NIMS database (see Figure C-2) without any relation to the monotonic data.

Figure C-2: Original NIMS data for Grade 91

Table A1. Monotonic and cyclic stress-strain properties¹⁾ of ASTM A387 Grade 91 steel plate.

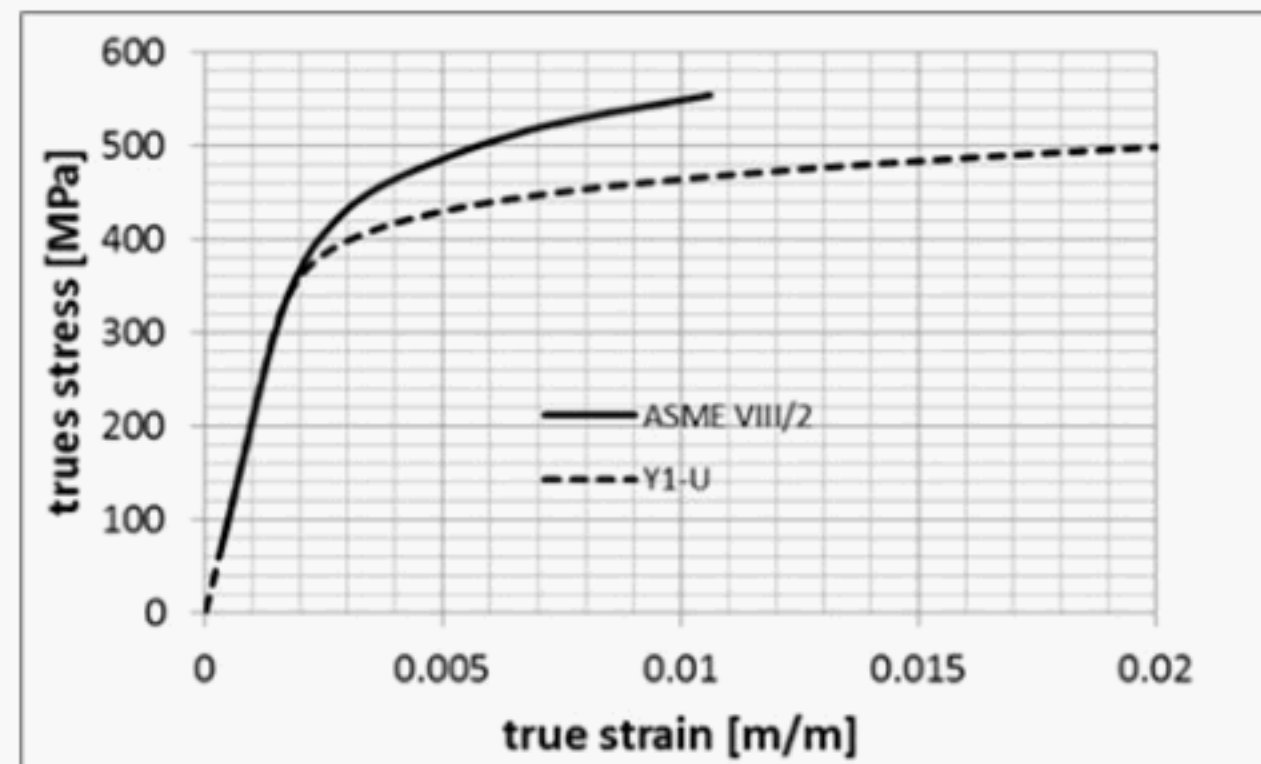
- n and C : exponent and coefficient (N/mm²), respectively, for monotonic stress-strain relation $\sigma = C\epsilon_p^n$, by tensile test under a strain rate of $5 \times 10^{-5} \text{ s}^{-1}$
- n' and C' : exponent and coefficient (N/mm²), respectively, for cyclic stress-strain relation $\sigma_a = C'\epsilon_{pa}^{n'}$, by incremental step test
- E : Young's modulus (kN/mm²) determined by cycling in the elastic domain before the test
- σ, σ_a : stress (N/mm²)
- $\epsilon_p, \epsilon_{pa}$: plastic strain

Test temperature (°C)	Monotonic stress-strain properties			Cyclic stress-strain properties	
	n	C	$E^{2)}$	n'	C'
RT	0.047	710	215	0.117	975
500	0.066	594	180	0.132	693
550	0.054	482	172	0.142	609
600	0.042	330	158	0.121	443
650	0.071	269	140	0.125	343

- 1) Monotonic and cyclic properties were determined by linear regression analysis of $\log \sigma$ to $\log \epsilon_p$ for plastic strains from 0.1×10^{-2} to 1.7×10^{-2} and from 0.05×10^{-2} to 0.91×10^{-2} , respectively.
- 2) The values of Young's modulus are arithmetical means, and the standard deviations are approximately 5 kN/mm² for each temperature.

Using the Japanese coefficients and exponents, it becomes obvious that YS monotonic is 530 MPa, and YS cyclic is 471 MPa (cyclic softening). These numbers are therefore only valid for a YS of 530 MPa. Using a material with different monotonic YS (e.g., ASME Table IID-values) would therefore lead to a different cyclic YS (which must be below the monotonic YS). Otherwise the material would look like cyclic hardening instead of cyclic softening (see Figure C-3)

Figure C-3: Comparison of cyclic and monotonic stress-strain curves for 9Cr-1Mo (grade 91) in current code edition



Note: Without scaling the material is expected to cyclic harden (replotted from ASME ST-LLC's STP-PT-056).

Cyclic stress-strain curves must be therefore always be considered in context with the monotonic stress-strain curve for the material under consideration. Otherwise non-conservative assessments of the influence of cyclic loading could arise.

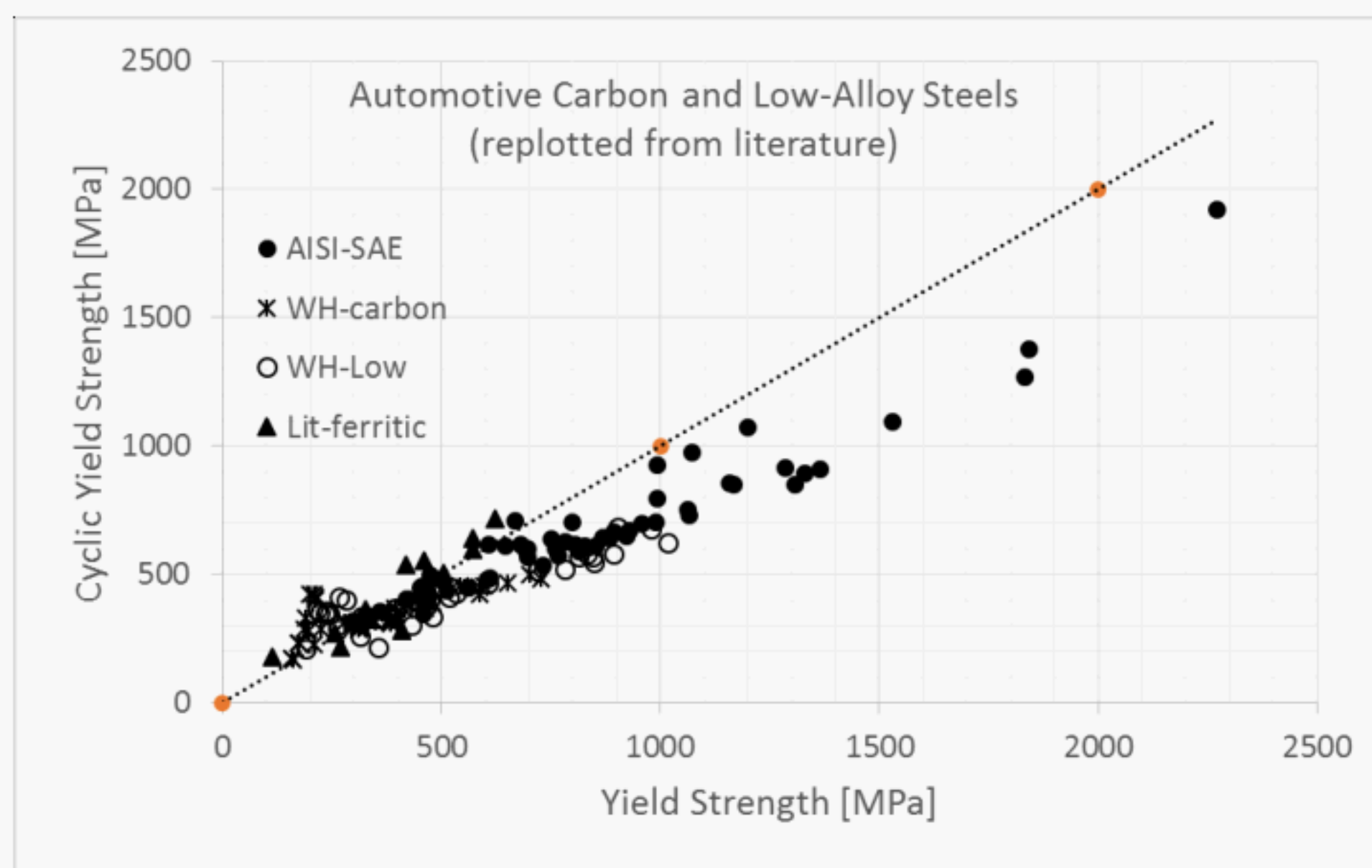
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APPENDIX D: EXAMPLES FOR VALIDITY OF CONCEPT

D.1 Carbon and Low Alloy Steels

Determination of cyclic stress-strain curves contains a high degree of uncertainty as already touched upon in the introduction. Therefore, comparisons of the results with comparable evaluations are an important measure to check the plausibility of the results. Figure D-1 compares literature data for carbon steels and low alloy steels (AISI-SAE, Lit-ferritic) and the current investigation (WH-carbon, WH-Low). The straight line represents $Y_S' = Y_S$. Taking into consideration that some literature results were obtained by digitization of data from a figure, it looks like there is a consistent picture concerning the average relation between monotonic and cyclic Yield Stress for these classes of materials. The data given in [5], [6] list also cyclic hardening exponents. The average value for carbon and low-alloy steels listed is 0.147. This number compares extremely well with 0.148, which is the average calculated in the current evaluation.

Figure D-1: Comparison of the results of this investigation with literature data



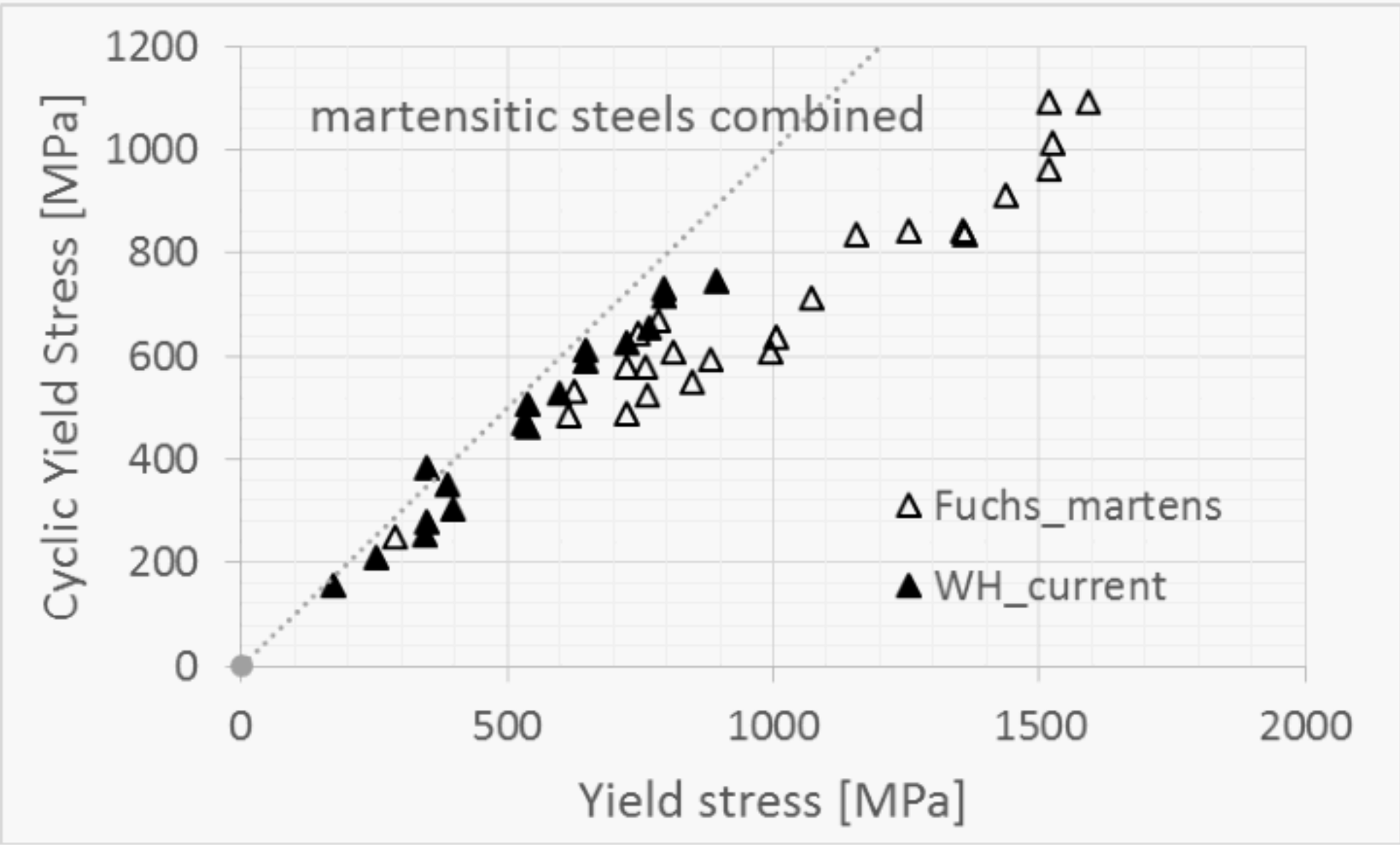
Notes: AISI-SAE [6]=carbon steels and low alloy steels, Lit-ferritic [4]=ferritic-pearlitic steels, WH-carbon=carbons steels this evaluation, WH-Low=low alloy steels this evaluation

D.2 Martensitic 9-13% Cr-Steels

Figure D-2 shows literature data (Fuchs-martens) together with data from the current investigation (WH_current). Also for this class of materials a good agreement was found.

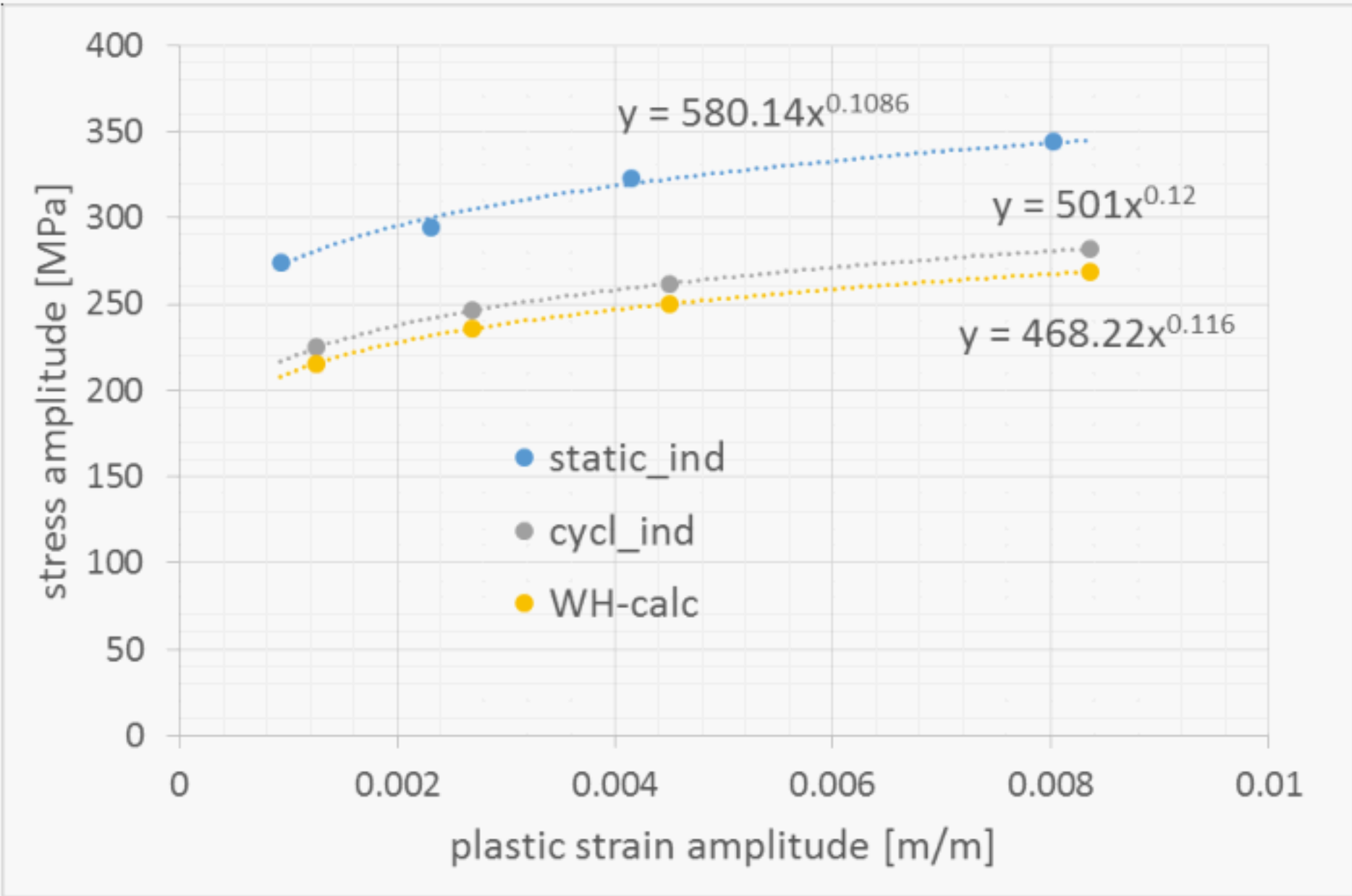
The modified 9Cr-1Mo type steel grade 91 was taken as another example. The data were taken from an Indian investigation [12] and they were not used for the current evaluation. The tests were performed at 550° C. Figure D-3 compares the cyclic stress-strain curve from the Indian investigation (cycl_ind) with the prediction from the current investigation (WH-calc) and a very good agreement was found. For a demonstration of cyclic softening, the monotonic curve (as given in the Indian paper) is also shown.

Figure D-2: Comparison of the results of this investigation with literature data



Note: Fuchs-martens - Literature [4]; WH_current - this evaluation

Figure D-3: Monotonic and cyclic stress-strain curves of a grade 91 martensitic steel

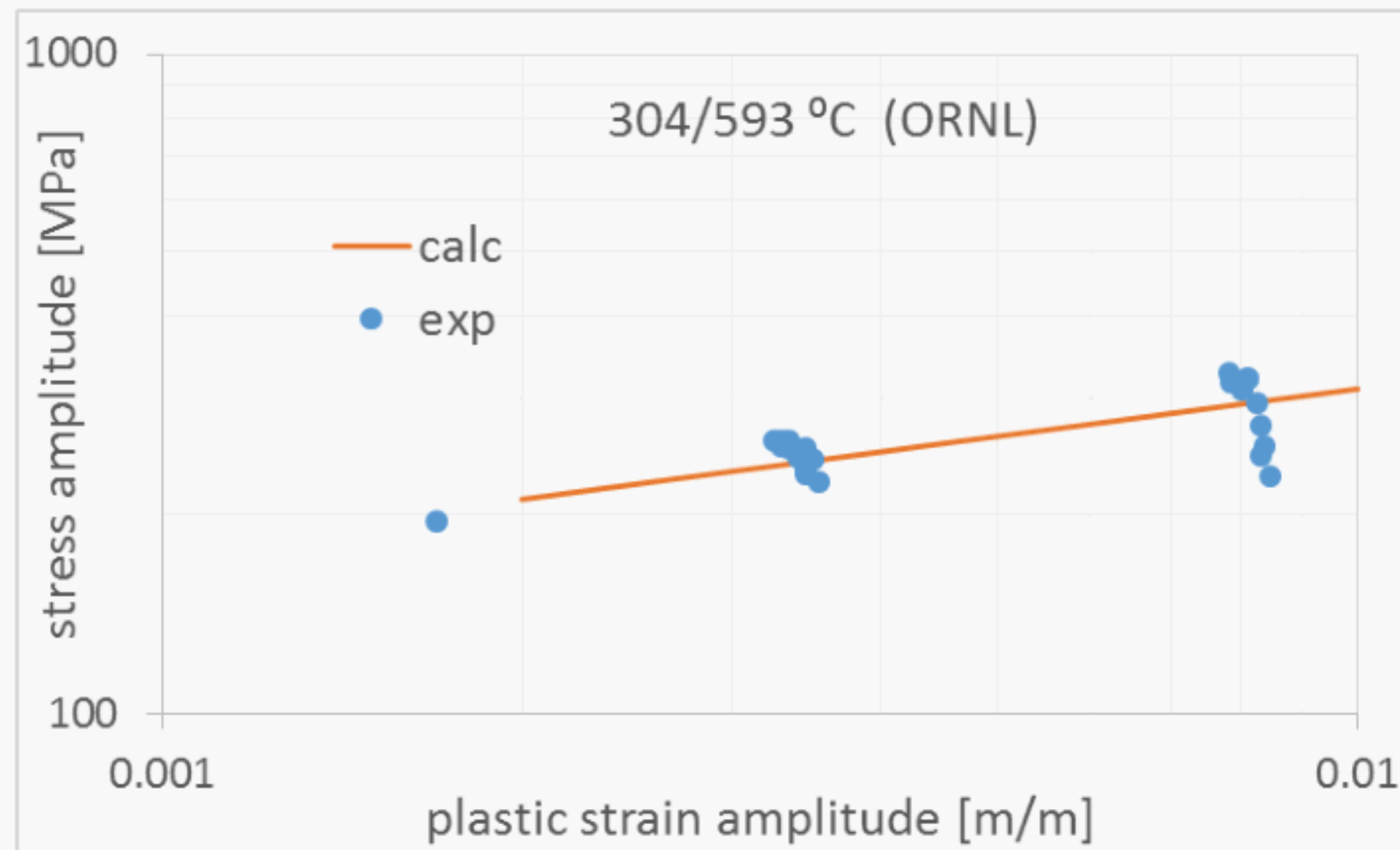


Note: Static_ind=monotonic stress-strain curve [12], cycl_ind=cyclic stress-strain curve [12], WH-calc=current report

D.3 Austenitic Steels

The validity of the relationships for austenitic steels was tested, taking results of 304-steel tested at 593° C into consideration [13]. The experimental values (exp) are compared with the calculated values (calc) in Figure D-4 and a very good agreement was found.

Figure D-4: Comparison of measured (at 593°C) cyclic stress-strain values for 304 (exp) [13] with the prediction based on the current report (calc)



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