TENSTAND - WORK PACKAGE 4 - FINAL REPORT

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1. Introduction

Tensile testing according to EN 10002-1 is one of the basic mechanical tests to characterise the mechanical properties of metallic materials. This testing procedure has been regularly under development for many decades in order to modify and amend it and to bring it up to an up to date standard. Today tensile testing for quality control in metals manufacturing industry is routinely performed automatically with computer controlled testing machines. Due to economical needs of industry proposals were made by a European Standard Committee to amend the standard EN 10002-1. A European research project with the acronym TENSTAND was started to validate the proposed modifications of the tensile testing standard. The work package 4 of the project was to validate the machine control characteristics. A comparison test program was started between the project partners to compare experimental results according to the proposal to modify the standard EN 10002-1. Initially testing in the strain control mode was introduced as well as switching of the control mode to crosshead control[1] and switching of the testing speed at appropriate points during the test. The comparison test was evaluated statistically and scientifically. Conclusions were derived from the comparison test and summarised as recommendations to the standard committees.

2. European development of the tensile testing standard EN 10002-1

In the following report the development of the tensile testing standard which has been under development for the last a few years will be explained. Due to the industrial needs to perform a tensile test more economically the time taken for a tensile test must be shortened. Thus the allowed testing speed in the tensile test was increased which has already been introduced into the standard a few years ago. The European standard EN 10002-1 has been continuously developed by the European Committee for Iron and Steel Standardisation, Technical Committee 1, Working Group 1 (ECISS TC1 WG1). Because of the existing scatter of the material properties obtained from tests performed according to the existing valid version of the standard EN 10002-1 it was proposed that for an amendment of the testing procedure in order to reduce the scatter. Thus the proposal was to conduct the tensile test initially in the strain controlled mode where the allowed testing speeds must be adapted. Figure 1 shows the proposal of the ECISS TC1 committee at the beginning of the TENSTAND project. Additionally the standard EN 10002-1 should be harmonised with the international tensile testing standard ISO 6892 [1]. Primarily the interests of USA and Japan with their national standards must be taken into account this will be undertaken by the ISO TC164 SC1 committee.

3. Validation of the machine control characteristics

Within work package 4 of the TENSTAND project a comparison test program was conducted between the project partners and two additional industrial associated partners of the project. The aim of the comparison test was to obtain answers to the following questions:

- Does the new proposal for the tensile testing standard minimize the scatter of the material properties?
- Are the partners able to perform tensile tests in the proposed way?
- Are there differences in the materials properties for strain controlled and crosshead controlled testing?
- How sensitive are the materials properties with concern to the testing speed?

[1] Equivalent vocabulary to crosshead control is displacement control, position control

3.1 The comparison test program

The comparison test program does not fully fulfil the requirements according to the standard ISO 5725-2 for a round robin test. Thus it was decided to perform a comparison test program involving twelve partners.

3.2 The test materials

Two different types of materials were selected for testing: materials with upper and lower yield strength and materials with 0.2% proof strength. These materials would represent important types of materials with concern to their properties within the testing standard. The materials were mainly proposed by the industrial project partners and were agreed by the consortium. The materials to be tested were as follows:

a) Aluminium alloy: AA5754, thin sheet material: thickness 1.2 mm, supplied by Hydro Aluminium, Bonn, Germany,
b) Steel: ZStE180, thin sheet material: thickness 0.95 mm, supplied by Thyssen Krupp Stahl, Duisburg, Germany,
c) Steel: DX56, thin sheet material: thickness 0.7 mm, supplied by Thyssen Krupp Stahl, Duisburg, Germany,
d) Nickel based alloy: Nimonic 75 (Certified Reference Material CRM 661), bar material: diameter 14 mm, supplied by National Physical Laboratory, Teddington, UK,
e) Steel: S355, thick sheet material: thickness 20 mm, supplied by CORUS,
f) Stainless steel: SS316L, thick sheet material supplied by CORUS.

The homogeneity of the materials was not tested within the TENSTAND project.

3.3 The test pieces

To cover a wide field of industrial applications four different test piece geometries were selected to be tested. In detail they were as follows:

- ISO 12.5 x 50 mm (materials AA5754, ZStE180, S355),
- ISO 20 x 80 mm (materials AA5754, ZStE180, DX56),
- Ø 10 x 50 mm with M16 thread (materials S355, SS316L),
- Ø 10 x 50 mm with M14 thread (material Nimonic 75).

The test piece geometries are shown in detail in figures 2 to 5. For the materials AA5754, DX56 and ZSt180 the test pieces were taken from sheet material perpendicular to the rolling direction. The test pieces of the material S355 were taken parallel to the rolling direction. The flat ISO12.5x50 test pieces were taken in that way that the width of the test pieces is equal to the thickness of the sheet. The Nimonic 75 test pieces were taken from bars parallel to the bar direction.

3.4 The test matrix and test parameters

The testing was planned for 12 partners with 6 materials and 4 test piece geometries. Two partners did not do any testing and are therefore removed from the test matrix. To economise it was agreed that only one material would be tested by every partner. The other materials would be distributed among the partners with a minimum of 4 partners testing any one material. One partner would test every material. To get a minimum of statistics each test would be performed with 5 test pieces. The whole test matrix is shown in Figure 6 showing the number of test pieces actually tested by each laboratory.

The test parameters are subdivided into two parts, materials with upper and lower yield strength (indicated with 1) and materials with 0.2 % proof strength (indicated with 2). The test matrix contains the upper and the lower bound areas of the allowed testing speed of the ECISS proposal which was the actual version at that time.

Test program for materials with 0.2%-proof strength

1.1 S**train control** 0.00025 s^{-1} strain rate and determination of $R_{p0.2}$, then displacement control at equivalent 0.008 s^{-1} strain rate to failure and determination of R_m (EN 10002-1 new proposal).

1.2 D**isplacement control** (crosshead) equivalent 0.00025 s^{-1} strain rate in elastic range and determination of $R_{p0.2}$ then displacement control at equivalent 0.008 s^{-1} strain rate to failure and determination of R_m (EN 10002-1:2001)

1.3 S**train control** 0.00025 s^{-1} strain rate and determination of $R_{p0.2}$, then displacement control at equivalent 0.00025 s^{-1} strain-rate until failure and determination of R_m.

Test program for materials with upper and lower yield strength

2.1 S**train control** 0.00025 s^{-1} strain rate up to R_{eH}, then displacement control at equivalent 0.002 s^{-1} strain rate up to end of yield and determination of R_{eL}, then displacement control at equivalent 0.008 s^{-1} strain rate to failure and determination of R_m.

2.2 D**isplacement control** equivalent 0.00025 s^{-1} strain rate up to R_{eH} then displacement control at equivalent 0.002 s^{-1} until end of yield and determination of lower yield R_{eL}, then displacement control at equivalent 0.008 s^{-1} strain rate to failure and determination of R_m.

2.3 S**train control** 0.00025 s^{-1} strain rate up to R_{eH}, then displacement control at equivalent 0.00025 s^{-1} strain rate up to failure and determination of R_{eL} and R_m.

3.5 Instructions for testing within the comparison test program

When starting the comparison test program the partners involved were given a set of instructions. It contained the delivery list, instructions and data file templates with Excel and ASCII formats. The instructions are shown in Annex A, 1, 2, 3 and 4.

4. Results of the comparison test

The comparison test program was started at the end of February 2003. Originally the completion of testing was envisaged to finish at the end of April 2003. However most partners encountered various problems and consequently the results were delivered late. By 1st July 2003 only 36% of the results had been received. Subsequently the number of results increased very slowly and it was decided to prolong the project because of this delay. The last results were received one week before the final meeting took place at March 8-9th 2004 in Berlin.

4.1 The received results and data processing

Approximately 90% of the expected results were received. The total numbers of test pieces that were tested were 811. Some of the partners failed to send back the tested test pieces. The same types of problems were encountered by those partners who brought them to notice. Various issues were clearly identified: difficulties to conduct closed loop strain controlled testing, to implement the control mode switch, to achieve the allowed testing speed, to record the recommended and required data, to adjust the data acquisition rate, to evaluate the material properties with sufficient software and to measure the E modulus within a tensile test. Sometimes the data format was ignored and the data files had to be reformatted for further evaluation.

A considerable amount of comment sheets were attached to the test results where problems during testing were explained. This raises questions about the validity of these test results.

The received data were stored in a database at BAM with efficient functions to handle the data. Figure 7 shows a flow diagram with the various different steps of the data processing.

4.2 Application of statistics

According to the standard ISO 5725-2 [2] the comparison test program does not fully fulfil the requirements for a round robin test. All the same statistics were applied for the evaluation at the comparison test programme. In some cases the testing time exceeded the required rate quite dramatically, the validity of the test results is therefore questionable, reference values of the tested materials were not determined before beginning the comparison test, the scatter of the natural material properties were unknown except for that of Nimonic 75 [3].

The application of statistics is briefly described in the following. A great amount of parameters have to be taken into account:

- 5-6 material properties ($R_{p0.2}$, E, R_m, A_g, A or R_{eH}, R_{eL}, E, R_m, A_g, A)
- 3 different test parameters
- 3 (4) different test piece geometries
- 6 materials

The received results must be prepared for evaluation. To determine outliers the Cochran test was applied. The Cochran's test value C is

$$C = s_{\max}^2 / \sum s^2$$

with s as the standard deviation. C is tabled in dependence of the number of the repeated tests. When an outlier was identified by the Cochran test, it was decided on an individual basis how to treat these results. Occasionally only the individual outliers were taken into account and in some cases the whole test was identified as an outlier. Figure 8 shows an example for the application of the Cochran test. On the left side the acceptable area can be seen, in the middle the straggler area lies between the 95% and 99% confidence and on the right side the area for outliers is determined. When an outlier has to be removed the mean values must be calculated again without the outlier being present.

4.3 The tensile test results for all materials and their interpretation

The terminology used in the following figures is briefly explained. On the left Y axis the stress values can be seen, at the bottom the letters for the anonymised laboratory identifiers, above these the numbers for the test parameters, where the first numeral indicates the materials with 0.2% proof strength (1) or the materials with upper and lower yield (2), the second numeral means the case according to chapter 3.4 with the different testing speeds and control modes. The top scale indicates the standard deviation achieved for every bar. The large columns indicate the mean value over all tests repeated in one lab, the small bar indicates the highest and the lowest value for that set of tests, i.e. the range of scatter.

Generally the influence of the control mode on $R_{p0.2}$ or R_{eH} can be investigated by the comparison of the results of test modes 1.1 and 1.2 or 2.1 and 2.2. The influence of testing speed on R_m and A can be shown by a comparison of the test modes 1.1 and 1.3 or 2.1 and 2.3. The influence of testing speed on the material properties R_{eH} and $R_{p0.2}$ is well known and has been debated in length for more than fifty years [4]. A significant amount of literature is also referenced in the final report of the work package 1 of the TENSTAND project [5].

4.3.1 The materials with 0.2% proof strength $R_{p0.2}$

In figures 9 and 10 the 0.2 % proof strength for the material DX56 can be seen with the ISO12.5x50 and the ISO20x80 test pieces. A trend is observed that a higher value of $R_{p0.2}$ can be seen for 9 of 10 sets of tests conducted in crosshead control (test mode 1.2) compared to initially strain controlled tests (test mode 1.1). The different labs have measured slightly different levels for $R_{p0.2}$ and the amount of scatter is also slightly different (0.45 – 2.65 MPa ≈ 0.28 – 1.66 %) but in all the differences are moderate. In figure 11 and 12 the ultimate tensile strength R_m is shown for the material DX56 with the large and small flat thin sheet test pieces. The R_m values for the tests conducted in crosshead control are slightly higher than for tests that began in strain control for 6 of 10 test sets, but this is not significant. The standard deviation varies between 0.45 and 3.01 MPa (≈ 0.15 – 1.02 %). However the test speed sensitivity of R_m can clearly be seen in all test sets. A higher testing speed leads up to approx. 7 % higher values of the R_m for the steel DX56 when comparing the results of test modes 1.1 and 1.3.

The results for the stainless steel 316L are shown in figures 13 and 14. These figures contain the results of $R_{p0.2}$ and R_m. The influence of the control mode is similar compared to that with the material DX56. Tests performed in crosshead control for 10 of 12 test sets attained a higher value for $R_{p0.2}$ compared to the tests performed initially in the strain control mode. The standard deviation was significantly higher than at the material DX56 (1.36 – 12.05 MPa ≈ 0.59 – 5.24%). The influence of the control mode on the determination of R_m is less significant but an influence of the testing speed on the values of R_m can be clearly seen. Lower testing speeds lead to approx. 4 – 5 % higher values of R_m. This is the inverse behaviour compared to the steel DX56. The standard deviation was in the range of 2.10 and 7.49 MPa (≈ 0.37 – 1.31 %).

For the Nickel based alloy Nimonic 75 the tensile test results of $R_{p0.2}$ and R_m can be seen in the figures 15 and 16. A few results are missing for the test parameters 1.2. The reason for that was the limited availability of Nimonic 75. As a consequence there is a limited amount of results for evaluation. For 3 of 4 sets where results are available for all three test modes, the tests in crosshead control show higher values for $R_{p0.2}$ compared to the tests performed in strain control mode (see modes 1.1 and 1.2). This is consistent with the results of the materials mentioned before. The standard deviation lies between 0.71 – 8.53 MPa (≈ 0.24 – 2.84 %). The influence of the testing speeds on the R_m is also clearly visible. With lower testing speed up to approx. 1.5 % higher values of the R_m are found for all test sets (see test modes 1.1 and 1.3). The standard deviation of R_m had values between 0.54 and 6.72 MPa (≈ 0.07 – 0.89 %).

The last material with 0.2 % proof strength is the Aluminium alloy AA5754. The tensile test results of $R_{p0.2}$ and R_m are shown in the figures 17 to 20. No influence of the control mode on the determination of $R_{p0.2}$ is visible (figures 17 and 18). The standard deviation varied between 0.21 and 1.57 MPa (≈ 0.2 – 1.48 %). But the influence of the testing speed on R_m can clearly be seen. For lower testing speed R_m is found to be up to approx. 5 % higher in 9 of 9 test sets (figures 19 and 20). The standard deviation was between 0.50 and 2.87 MPa (≈ 0.24 – 1.37 %).

4.3.2 The materials with upper (R_{eH}) and lower (R_{eL}) yield strength

A material with upper and lower yield strength that has been investigated is the alloy ZStE180. The influence of the control mode on the determination of R_{eH} is not visible with regard to the figures 21 and 22. The behaviour is not uniform. For the test parameters 2.1 and 2.3 an identical behaviour is anticipated because the same testing speed and control mode was used. But a significant number of tests show differences. This will be explained later in chapter 4.5. It can be seen in figure 22 there is a large difference in mean values of R_{eH} between the individual laboratories, a spread of 40 MPa (approx. 16 %). The standard deviation of the mean values varied between 1.87 and 8.81 MPa (≈ 1.87 – 3.39 %). The different test pieces were tested by different labs. Thus an influence of the test piece geometry cannot be evaluated. The results for R_{eL} are shown in figures 23 and 24. Again for the test parameters 2.1 and 2.3 differences in the R_{eL} values can be seen but will not be explained here. The influence of testing speed becomes visible. For a lower testing speed an up to approx. 7 % lower value of R_{eL} is observed for 8 of 9 test sets. The standard deviation varied between 0.94 and 6.62 MPa (≈ 0.41 – 2.88 %). For the determination of R_m the results are shown in figures 25 and 26. The standard deviation was between 0.45 to 3.53 MPa (≈ 0.14 – 1.07 %) for the majority of the tests. The influence of the testing speed on R_m values was significant for all labs and all tests. With lower testing speed up to approx. 4 % lower R_m values were observed.

The results of the steel S355 are shown in figures 27 to 32. For the influence of the control mode on the determination of R_{eH} a clear trend was not observed (figures 27 and 28). The behaviour of the tests cannot be considered as uniform. Some differences were observed between the test parameters 2.1 and 2.3 which cannot be explained because the same testing speeds were used for the determination of R_{eH}. The standard deviation varied between 2.58 and 25.46 MPa (≈ 0.61 – 5.99 %). The influence of testing speed on R_{eL} for 12 of 15 test sets was an affect giving use to approx. 3 % lower values of R_{eL} with a lower testing speed (fig. 29 and 30). The standard deviation sat between 0.87 and 10.52 MPa (≈ 0.21 – 2.6 %). For all tests the influence of testing speed on R_m can be seen (fig. 31 and 32). For higher testing speed up to approx. 2 % higher values of R_m were found (see modes 2.1 and 2.3). The standard deviation lied between 1 and 7.17 MPa (≈ 0.18 – 1.27 %).

4.4 Normalised test results

The next set of figures shows normalised test results. This means that for one material and test piece geometry the results of all partners were calculated to a mean value and the results of the test parameters 1.1 or 2.1 were set to 100 % as the reference. Then the mean values of the test parameters 1.2 and 1.3 or 2.2 and 2.3 were calculated relative to this reference. Additionally the scatter of values is shown as the mean value + 2S and – 2S which represent the 95% confidence interval.

Normalised test results for 0.2% proof strength $R_{p0.2}$

For the material DX56 the trend observed in chapt. 4.3.1 remains present when the results of all labs were averaged. Generally higher values for $R_{p0.2}$ were found for tests in crosshead control in comparison to strain control (fig. 33). The mean values of the tests conducted in different control modes varied in the range of approx. +1 to +4 %, the scatter was approx. ± 2 to ± 4 %. A clear trend for the scatter was not observed for strain controlled and crosshead controlled tests.

The normalised $R_{p0.2}$ values of the material SS316 are also shown in fig. 33. The observed trend is similar to that of the material DX56. The tests performed in crosshead control showed a higher value compared to tests in strain control. These results are comparable with fig. 13. There was a significant scatter for strain controlled tests of approx. ± 4.5 to ± 8 % (test mode 1.1 and 1.3) and that of crosshead controlled tests is laid within this range.

Figure 33 also contains the results for the material Nimonic 75. With concern to the influence of the control mode there is a tendency which leads to higher values for $R_{p0.2}$ for tests in crosshead control but this influence is relatively small (approx. 1 %). No clear trend was observed for the scatter of the mean values between the different test modes.

The results of the aluminium alloy AA5754 can also be seen in this figure. Here a clear trend for the influence of the control mode on $R_{p0.2}$ cannot be seen because it is lower than 1 %. Unexpected differences were observed between results of the test mode 1.1 and 1.3 for both test piece geometries. The scatter of the mean values received in crosshead control is slightly higher compared to strain controlled tests.

Normalised upper yield strength R_{eH}

The results for the material ZStE180 are shown in figure 34. An influence of the control mode is not observed (see test modes 2.1 and 2.2). Unexpected differences of approx. 3 - 4% are observed for the different control modes 2.1 and 2.3. The scatter is observed in the range from approx. ±5.5 to ±11.5%.

For the material S355 no clear trend for the influence of the control mode can be seen (fig. 34). The scatter lies in the range from approx. ±6% to ±7.5%.

Normalised lower yield strength R_{eL}

The normalised test results for the material ZStE180 can be seen in figure 35. An influence of the control mode on the determination of R_{eL} cannot be derived clearly because the differences are small (< 1 %). The scatter was approx. ±4 to ±7%. With a lower testing speed the values for R_{eL} were found to be 3 - 4% smaller indicating a sensitivity to testing speed.

Again for the material S355 no clear trend for the influence of the control mode can be seen (fig. 35). The mean values vary only a little bit more than 1 %. A scatter of approx. ±2.5 to 4% was observed. A small trend can be seen for the influence of testing speed. With lower rates smaller values of R_{eL} were obtained.

Normalised tensile strength R_m

In figure 36 the normalised test results for all materials are shown. The influence of the control mode on R_m is negligible for all materials because it is lower than 1 (see test mode 1.1 and 1.3 or 2.1 and 2.3). To show the influence of testing speed on R_m the materials can be divided into three groups:

- With lower testing speeds higher values for R_m were obtained. This is the case for the materials AA5754 and SS316L. Approx. 3.5 to 4 % higher R_m values were observed in this case.
- With lower testing speeds lower values for R_m were obtained. This is the case for the materials ZStE180, DX56 and S355. Approx. 1 to 5 % lower values for R_m were reached.
- Where no influence of the testing speed on R_m values was observed. This is the case for the material Nimonic 75. The differences were lower than 1 % and not significant.

Normalised percentage elongation after fracture A

The influence of the control mode and of the testing speed on the elongation A can be seen in figure 37. The influence of the control mode on A ranges from negligible to small and has values of approx. -1 to +3 % (see test modes 1.1 and 1.2 or 2.1 and 2.2). In some cases the elongation was observed to be slightly higher for crosshead controlled tests: AA5754 (2-3 %), DX56 (1-3 %). Others show changing behaviour: S355 (-1 to +2 %). For the material ZStE180 the influence is negligible. Where the scatter of the elongation after fracture is significant: AA5754 (approx. ±10 to ±15 %), ZStE180 (approx. ±3 to ±17.5 %), DX56 (approx. ±5 to ±10 %), Nimonic 75 (approx. ±3 to ±6 %), S355 (approx. ±13 to ±21 %), SS316L (approx. ±7 to ±10 %).

A trend for the influence of testing speed on A can be seen for all materials. For lower testing speed higher elongations were always observed: AA5754 (approx. 2-6 %), ZStE180 (approx. 6-9 %), DX56 (approx. 8-13 %), Nimonic 75 (approx. 3 %), S355 (approx. 3-7 %) and SS316L (approx. 31 %).

4.5 Detailed analysis and discussion of the data files and test results

Materials with 0.2 % proof strength $R_{p0.2}$

Some observations were noted with materials with 0.2% proof strength. In figure 38 stress-strain curves show different control modes each with different values for $R_{p0.2}$. To explain the 7 % difference it is essential to know the actual testing speed at the point where determination of the 0.2 % proof strength is taken. This is shown in figure 39 for the three test parameters. The black, red and blue lines show the stress-time curves for the three test parameters, the dotted lines show the corresponding strain-time curves. Here the lines are straight for strain controlled tests until determination of $R_{p0.2}$. This is equivalent to a constant strain rate. Under crosshead controlled tests the strain rate increases just after reaching the plastic region but before the determination of $R_{p0.2}$. This increase of the testing speed leads to higher values of $R_{p0.2}$ due to the change in stiffness of the test piece and the system stiffness when leaving the elastic region. This is a normal effect and cannot be avoided during testing in the crosshead control mode due to physical reasons. The crosshead control mode therefore shows a disadvantage for tensile testing of materials with $R_{p0.2}$. Looking to the influence of testing speed on R_m it can clearly be seen that with higher testing speeds higher values of R_m will be reached (figure 40). After increasing the testing speed the stress value is also higher. This remains consistently higher throughout the test affecting both R_m and A. The comparison of the testing speeds attained in both crosshead and strain controlled tests superimposed over the proposed testing speed is shown in figure 41. Here the curves for the stress (black), the strain (blue) and the strain rate (red) are shown versus time and the shaded areas represents the proposed testing speed. The curve for the testing speed is calculated by derivation of the strain-time curve. In this example the test was started with a correct testing speed but before determination of the proof strength $R_{p0.2}$ the testing speed is exceeded by approximately three times the allowed rate. After determining $R_{p0.2}$ the testing speed is further increased and initially lies within the allowed tolerances but by the time determination of R_m is measured the allowed testing speed has again been exceeded by approximately 15%. The reason for this is again the changing stiffness of the test piece and system. Exceeding the allowed testing speed raises problems about the validity of the test. Usually the testing speed is generally not checked after testing because easy and efficient tools to do this are generally not available with the software of the testing machine. With regard to the allowed testing speed, definitions could be provided in the tensile testing standard EN 10002-1 to avoid ambiguities. This is an example of one of the problems observed with the material DX56. For material AA5754 no problems were observed during the determination of $R_{p0.2}$. The reason for that lies in the shape of the stress strain curve (figure 42). As can be seen in the stress strain diagram of fig. 42 stress is relatively constant in the area for the determination of $R_{p0.2}$.

Materials with upper and lower yield strength R_{eH} and R_{eL}

For materials with upper and lower yield strength, irregularities were observed. Figure 43 shows stress-time and strain-time curves for ZStE180 conducted in mode 2.1 (strain controlled) and 2.2 (crosshead controlled). In the strain controlled mode it can be seen at the strain-time curves that the strain rate is unaffected when the test piece is deformed plastically. The strain-time curve is nearly straight which would indicate a constant strain rate during the phase when the R_{eH} is reached. Strain rate remains constant until the testing speed is increased. The switching to higher strain rate leads to a shift of the stress-time curve to higher values. This shift raises concern to the determination of the lower yield strength R_{eL}. The step in value could be misinterpreted as the lower yield strength R_{eL}.

Often the strain-time curve changes direction with the onset of plastic deformation for tests in the crosshead control mode. In some cases the strain rate decreases with the onset of plastic deformation, almost to zero for a few seconds. The reason for this may insufficient optimisation of the control parameters of the crosshead control mode or plastic deformation outside of the extensometer. In other cases an increase of the strain rate is observed. This may have its origin in the change of the stiffness of the test piece when it is plastically deformed. When switching to higher testing speed a shift of the stress time curve gives rise to the problem of detecting the lower yield strength properly.

Another example is shown in figure 44. For the strain controlled test the strain rate was constant until the peak stress R_{eH} was reached. Only for one test with the brown curve (test piece no 48Z-1) a smaller slope is observed during elastic deformation and the stress peak of the upper yield strength is missing. The reason for this behaviour may be bending of the test piece during testing. After switching the testing speed and the control mode a step in the stress-time curve is observed. This sudden increase in stress could be misinterpreted as R_{eH}.

On the right side of figure 44 examples for crosshead controlled tests are shown. The strain rate was increased despite no pronounced R_{eH} peak being attained, which resulted in a sudden rise in stress. Consequently this could be misinterpreted as R_{eH}. Interestingly in this example the Cochran test did not detect these tests as outliers. However detailed investigation of the ASCII data file showed that the tensile test did not meet the test parameters and the test software did not detect the material properties properly. For all the tests in this example the initial equivalent strain rate was too small by a factor of approximately 10. Additionally no pronounced upper yield strength is observed indicating that something went wrong during testing which was possibly due to bending of the test piece.

The next example is shown in figure 45. On the left picture the stress, strain and strain rate vs. time can be seen for the material ZStE180 in the strain controlled mode. After starting the test the strain rate of 0.025 %/s is reached within one second. Then the strain rate is constant until the onset of plastic deformation. The strain rate then increases due to the changing stiffness of the test piece. At this point the upper yield strength is detected. The testing speed is also increased at this point as the mode is switched to crosshead control. The strain time curve shows a small delay at the switching point and the strain rate time curve shows instability at this point. Then the strain rate at this point is 0.278%/s but should have been 0.2 %/s. In figure 45 on the right side the same test was performed on the material ZStE180 but purely in crosshead control (mode 2.2). The initial allowed testing speed was reached within a short time. It does not remain as constant as with the strain control mode but it is within the given rate. At the onset of plastic deformation the strain rate increases. After detection R_{eH} the separation rate is increased. The instability is smaller than for the strain controlled test at the point where the control mode was changed. A slight overshooting of the strain rate can also be seen before the strain rate stabilises. To summarise the two tests the stress, strain and strain rate versus time curves look similar. No pronounced advantage of the strain control mode was observed.

The measured strain rates of an initially strain controlled tensile test for the alloy ZStE180 is shown in figure 46 superimposed with the rate change blocks (shaded area). Up until the onset of plastic deformation the strain rate is within the allowed rate. A slight decrease in strain takes place as the test piece begins to deform. The machine subsequently increases the speed of the test but the rate surpasses the set rate considerably. This is the part of the test where the R_{eL} is to be measured. This higher rate naturally affects the value lower yield R_{eL}. In this area the allowed tolerances were exceeded indicating that the requested strain rate was not adjusted well to the equivalent crosshead speed. Additionally the strain rate was also not constant which may be due to the changing stiffness of the test piece during yielding. After switching to the final testing speed the strain rate is within the allowed tolerances but continuously increasing as the test progresses. In the area of R_m the strain rate exceeded the allowed tolerances and continues to rise until fracture.

In figure 47 the influence of the testing speed on the determination of R_m is shown for the material ZStE180 for the three testing modes. For the test mode 2.3 with a constant low strain rate the lowest value for R_m is observed. However for the tests with the higher strain rates a higher value of R_m was found.

4.6 Items that have not been investigated

The following aspects have not been investigated in the comparison test program:

- Influence of the homogeneity of the tested materials,
- The individual implementation of the tensile testing procedure in the labs,
- The properties of different tensile testing systems including grip systems,
- Inhomogeneous strain distribution at the test piece and the subsequent influence on the strain control of the testing machine.

5. Recommendations to the standard committees

The following recommendations should be made to the standard committees:

Upper yield strength R_{eH}

For the determination of the upper yield strength the strain control mode is recommended. Only in case of material anomalies such as the formation of Lueders bands, presence of Portevin Le Chatelier effects etc. should crosshead control mode be used.

Lower yield strength R_{eL}

No change of the testing speed is recommended between R_{eH} and R_{eL}. Switching from the strain control mode to the crosshead control mode may be possible if a stable mode switch can be realised.

0.2% proof strength $R_{p0.2}$

For the determination of the 0.2% proof strength the strain control mode is recommended.

Ultimate tensile strength R_m

Until the determination of the tensile strength R_m is completed the allowed strain rate should be limited to 0.0067 s^{-1} ± 20%. For this proposal the upper limit remains the strain rate 0.008 s^{-1} that has not to be exceeded.

Further recommendations

- For computer controlled tensile tests an ASCII data file should be recorded to allow a sufficient analysis after testing. The ASCII data file should contain the following four values and dimensions as a minimum: time [s], force/load [kN], strain [% or mm/mm] or extension [mm], travel/position [mm].
- For the data acquisition the data recording rate should be adjusted so that the material properties can exactly be determined. The procedure annexed in the EN 10002-1 should be amended to the up to date procedures that are currently available for modern tensile test systems.
- When an ASCII data file for a tensile test is available it is difficult to decide whether the test is valid or not. The definitions in the standard EN 10002-1 are somewhat weak and should be specified in more detail, especially with regard to the allowed testing speed and the number of data acquisition points for the determination of material properties.
- The testing software should be developed that a plausibility check for the tensile test can be performed automatically and easier by the testing operators:
  - The material properties should be checked,
  - The actual used and the allowed strain rates according to the standard should be compared e.g. in appropriate screen diagrams,
  - The points in the curve where the material properties have been determined automatically by software should be visualized in diagrams and marked in the ASCII data file e.g. in an additional data column by a flag,
  - The switching points of the control mode should be visualized in diagrams and marked in the ASCII data file e.g. also by a flag.

6. Conclusions

A comparison test program for computer controlled tensile testing has been conducted with 10 partners, 4 test piece geometries and 3 test parameters for 6 materials, partly with upper and lower yield strength and partly with 0.2 % proof strength. The aim was to validate proposals of the European standard committee ECISS TC1 WG1 with concern to strain controlled tensile tests to reduce the scatter of the material properties.

Statistical analysis of the material properties according to ISO5725 has shown that only few outliers were found. The majority of the problems during testing and the reasons for scatter of the material properties cannot be found by statistical analysis.

In practically every case all materials have been shown a dependency of the material properties on the testing speed. This has been raised since the allowed testing speed was increased in the standard EN 10002-1 a few years ago which was proposed by industry for economic reasons. The influence of the testing speed on the material properties of steels has been widely reported and described in literature [4]. The findings were to reduce and limit the range for the allowed testing speed for the determination of all material properties. When doing this the testing speed induced small scatter in the material properties.

Other reasons for the scatter of material properties have been found. With detailed analysis of all the tensile test data, difficulties during testing have been observed. In some tests the closed loop control mode was not optimised sufficiently, handling of the software was complicated and the unintended use of wrong software options has lead to unexpected results and errors. With missing time data the actual testing speeds cannot be checked.

Within the comparison test the scatter of $R_{p0.2}$ or R_{eH} is not significantly reduced by using the strain control mode instead of the crosshead control mode. Switching of the control mode must be avoided in the yielding range between R_{eH} and R_{eL} because of ambiguities for the determination of the material properties.

The scatter found in the material properties lies in the range of few percent and is blurred by the scatter of the homogeneity of the materials, and additionally due to the individual implementation of the tensile testing procedure in the labs, the effect of different tensile testing systems such as grip systems and probably inhomogeneous strain distribution at the test piece and the subsequent influence on the strain control of the testing machine. In total it is recommended to improve the quality of conducting a tensile test to reduce the scatter of the material properties. Different aspects may be taken into account to reach it. Test should be undertaken by well trained and qualified people who understand problems that may arise during a computer controlled tensile test.

The software for computer controlled tensile testing should be amended to be more user friendly. Methods to check a tensile test easily whether it is valid or not should be developed and introduced into software and testing standards.

7. Acknowledgements

All partners of the project were gratefully acknowledged for their engagement during testing and reporting within the comparison test program. The European Commission is gratefully acknowledged for financial support.

8. References

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[2] ISO 5725-2: Accuracy (trueness and precision) of measurement methods and results – Part 2: Basic method of the determination of repeatability and reproducibility of a standard measurement method (ISO 5725-2: 1994 including Technical Corrigendum 1:2002), The international Organisation for Standardisation (ISO), Geneve, Switzerland

[3] C.D. Ingelbrecht, M.S. Loveday, The certification of ambient temperature tensile properties of a reference material for tensile testing according to EN 10002-1 – CRM 661, European Commission, BCR information, Reference materials, Directorate-General, Joint Research Centre, EUR 19589 EN, 2000, ISBN 92-894-0482-5

[4] F. Körber, A. Krisch, Festigkeitsprüfung bei ruhender Beanspruchung, Handbuch der Werkstoffprüfung, 2ter Band: Die Prüfung der metallischen Werkstoffe, Hrsg. E. Siebel, Springer Verlag, Berlin, Göttingen, Heidelberg, 1955, pp. 35-91

[5] M.S. Loveday, T. Gray, J. Aegerter, Tensile testing of metallic materials: A review, Final report of the TENSTAND project of work package 1, April 2004

9. Tables and Figures

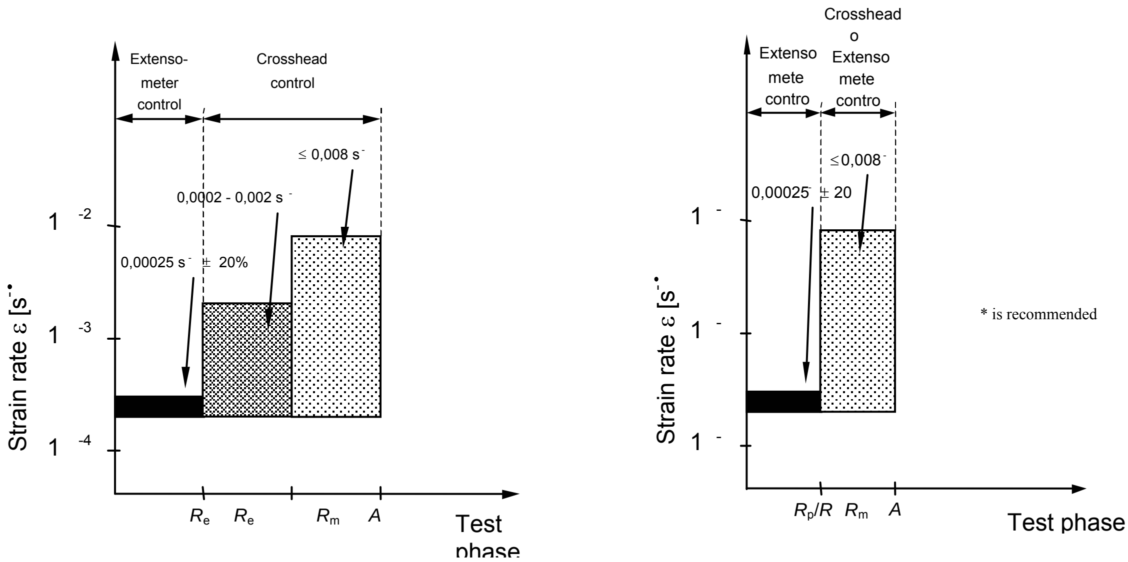


Figure 1: Proposal of ECISS TC1 WG1 to determine the allowed testing speeds for initially strain controlled tensile testing

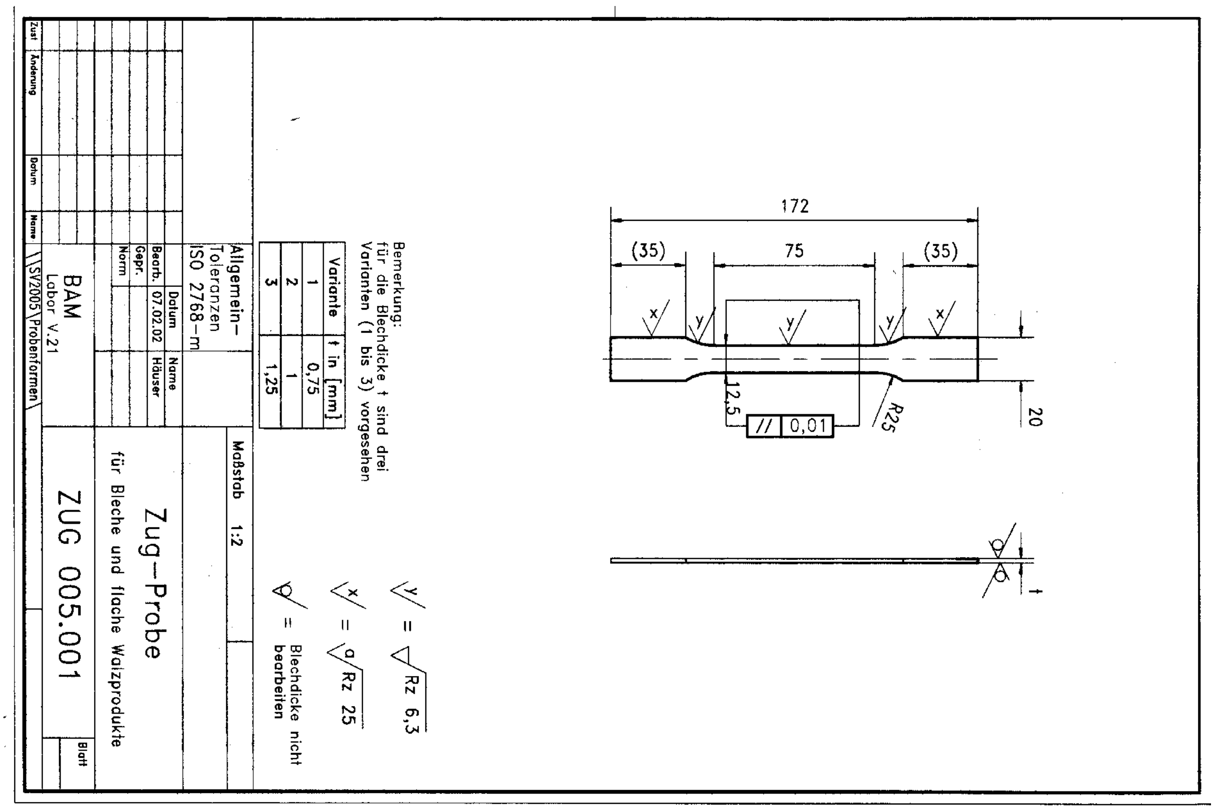


Figure 2: Test piece geometry ISO12.5x50 for flat samples of the materials AA5754, ZStE180, S355

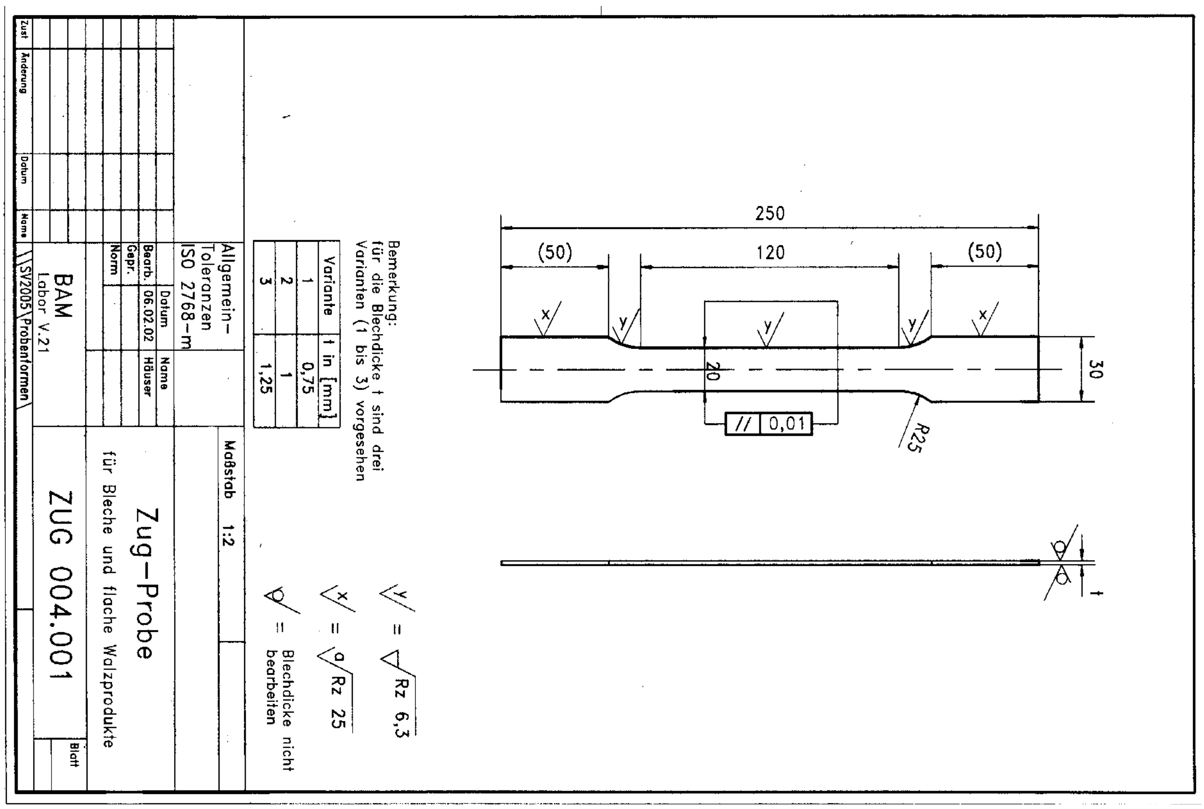


Figure 3: Test piece geometry ISO20x80 for flat samples of the materials AA5754, ZStE180, DX56

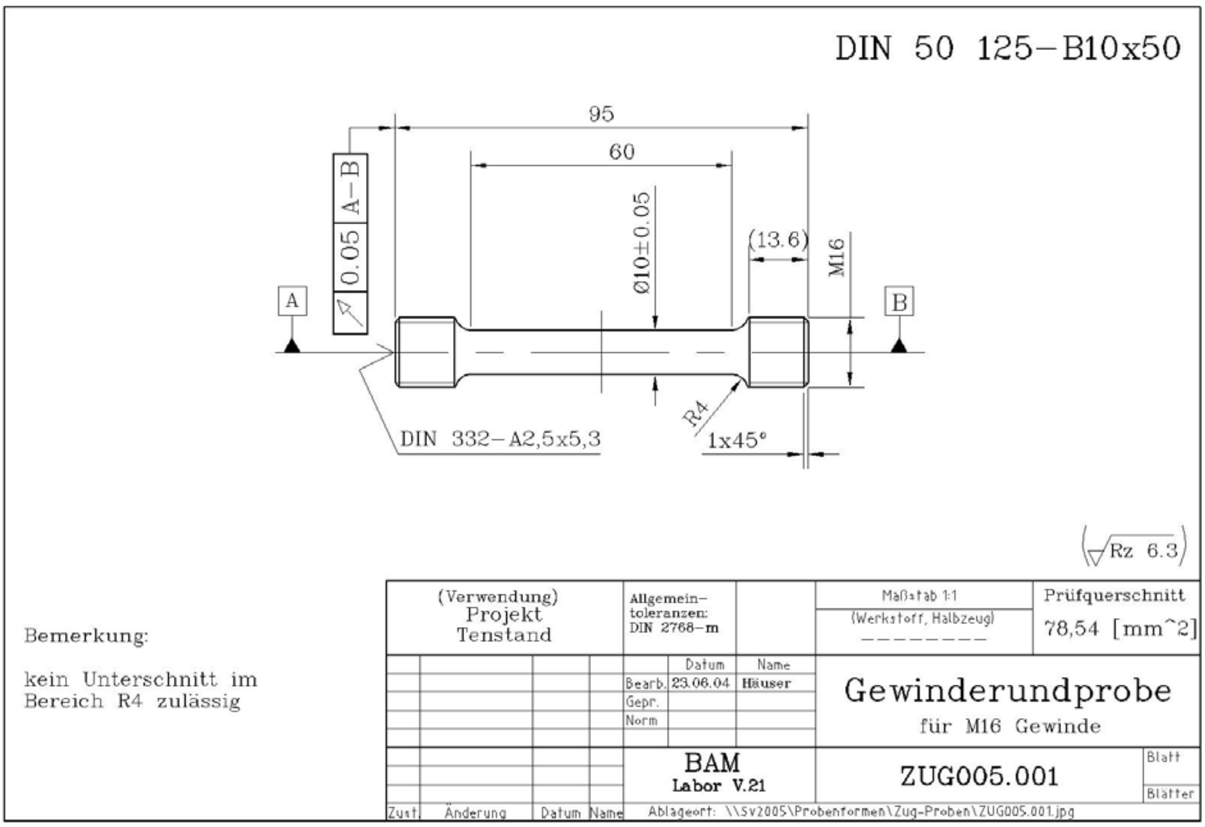


Figure 4: Test piece geometry according to DIN 50125 for cylindrical threaded samples of S355 and 316L

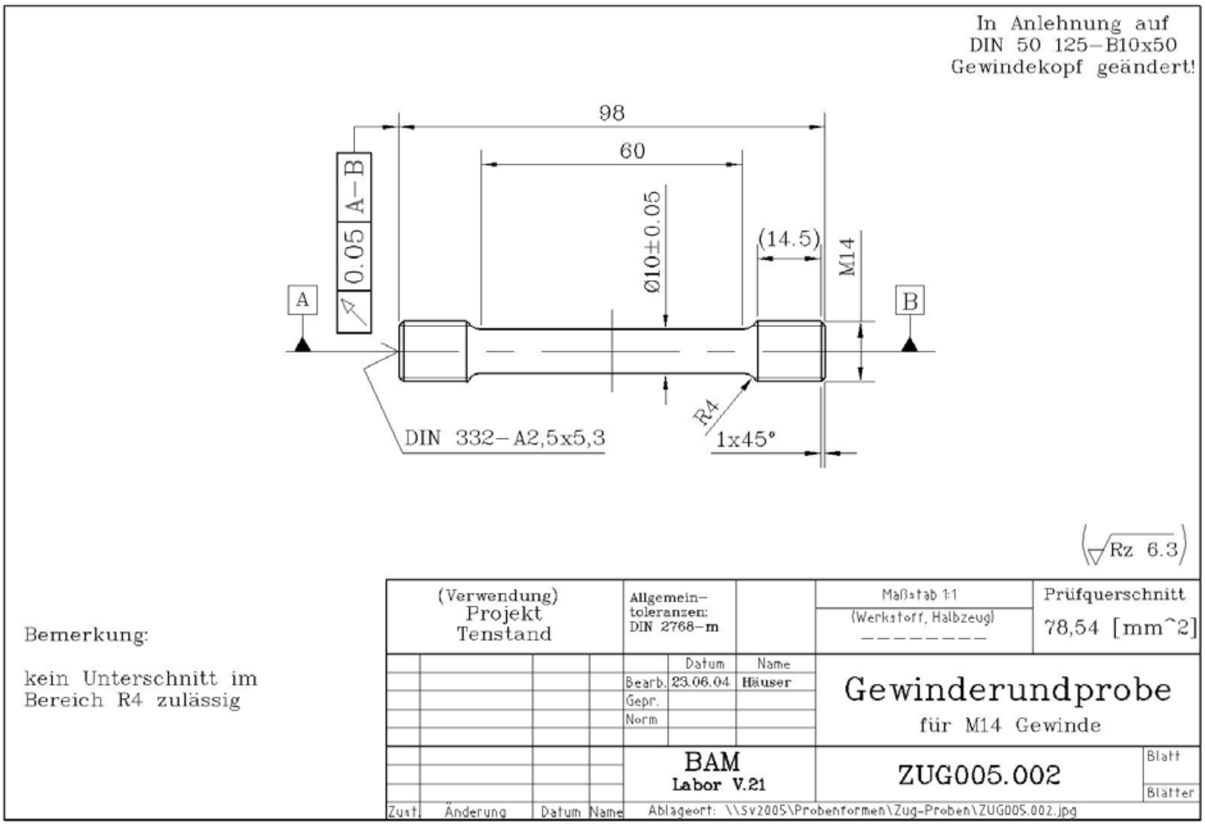


Figure 5: Test piece geometry according to DIN 50125 but with M14 thread for cylindrical threaded samples of Nimonic 75

Test materials	Ref. No.	Test piece geometry	Laboratory										No. of Labs	No. Pieces Tested
AA5754	1	ISO 12.5x50		11		15				15	15		4	56
	2	ISO 20x80		14		15	14	12				15	5	70
ZStE 180	3	ISO 12.5x50				15		13		15	15		4	58
	4	ISO 20x80		15		15		13	15			15	5	73
DX 56	5	ISO 12.5x50				15		13		14	15	15	5	72
	6	ISO 20x80		15		15		13	15			15	5	73
Nimonic 75	7	M14, 10x50	10		10	15	15	8		14	10	15	9	97
S355	8	M16, 10x50	15		15	15	15			15	15		6	90
	9	ISO 12.5x50	15	15	15	15	15	13	15	14	15	15	10	147
SS316L	10	M16, 10x50	15		15	15	15				15		6	75

Figure 6: Test matrix with test materials, test piece geometries; the partners are anonymised

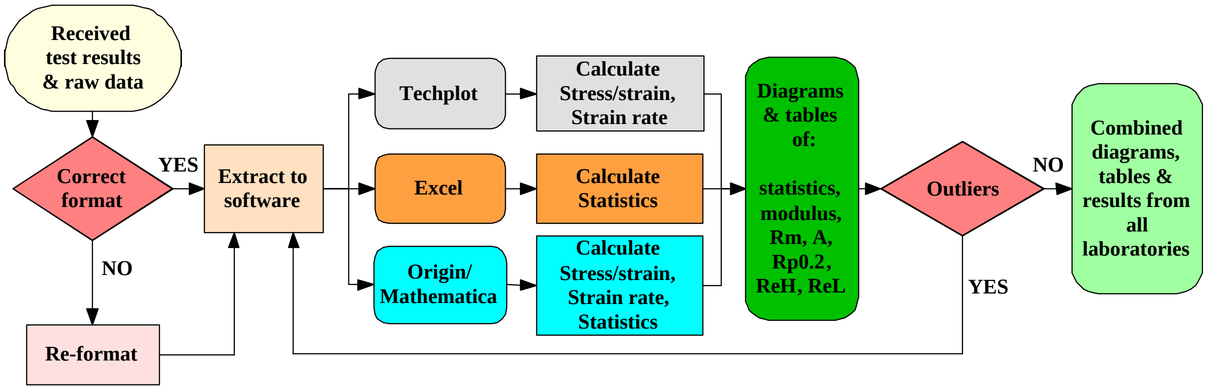


Figure 7: Flow diagram with different steps for data treatment during evaluation of the TENSTAND work package 4 comparison test

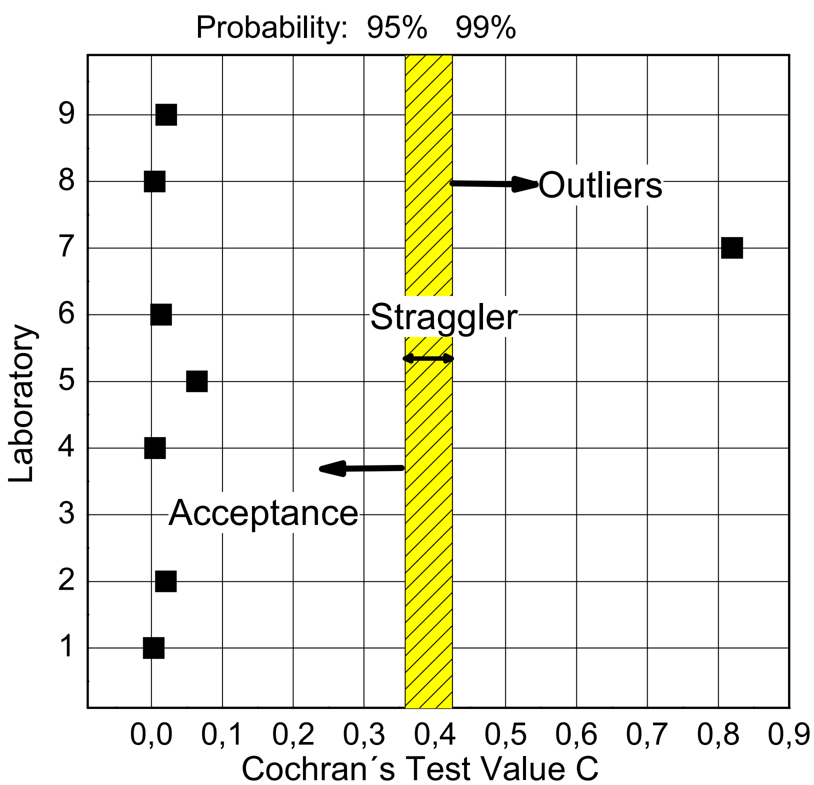


Figure 8: Cochran test for the determination of an outlier

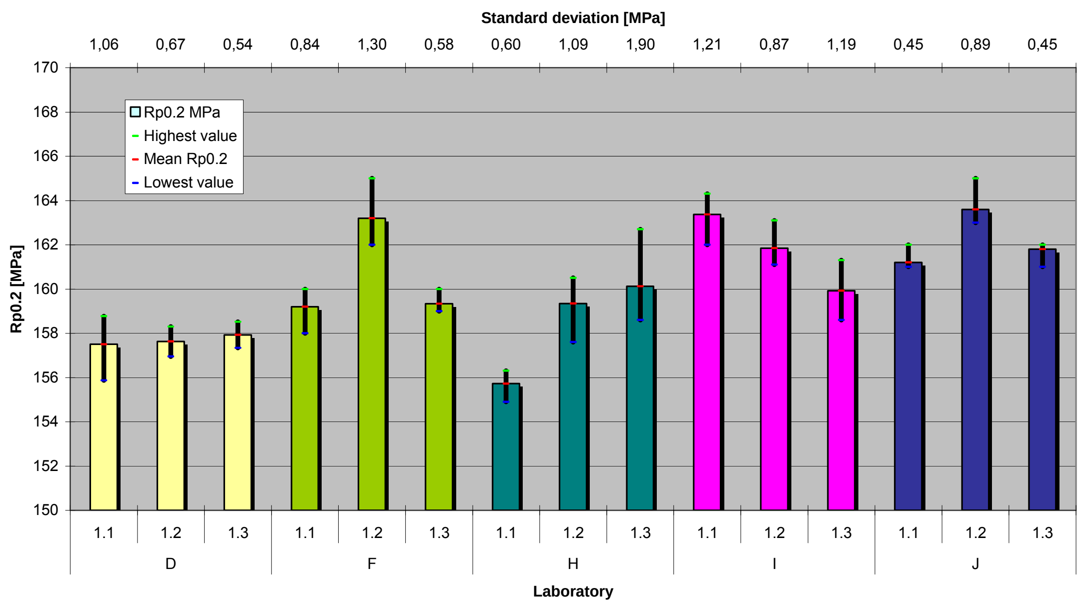


Figure 9: $R_{p0.2}$ for material DX56 with ISO 12.5x50 test pieces and extracted outliers

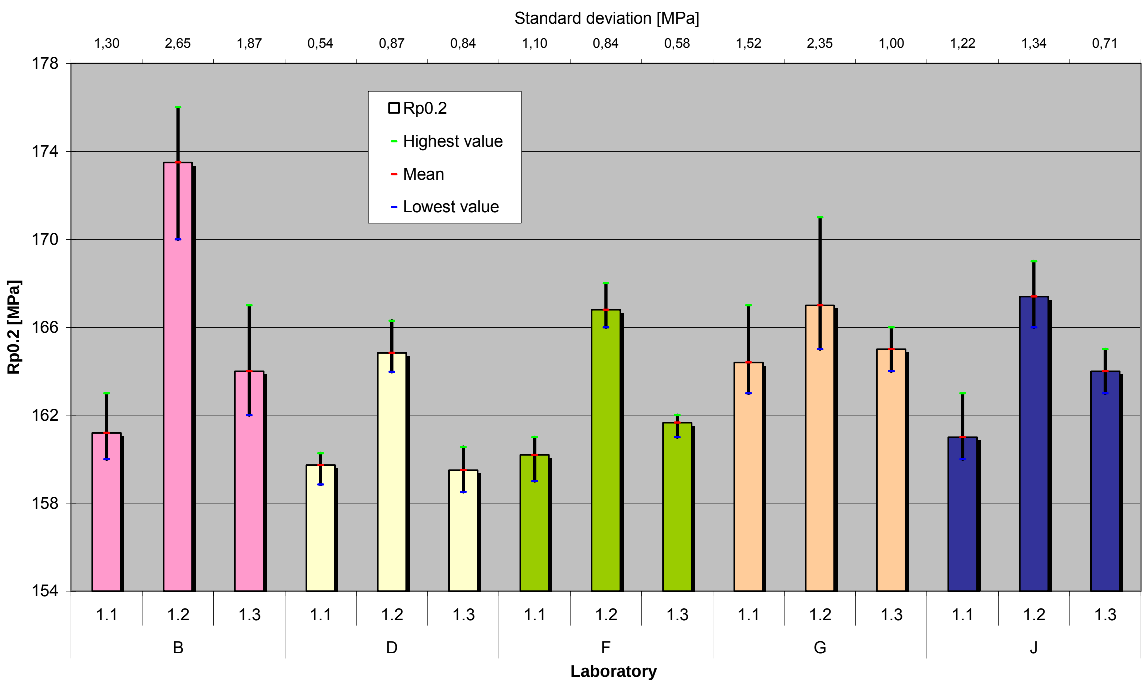


Figure 10: $R_{p0.2}$ for material DX56 with ISO 20x80 test pieces and extracted outliers

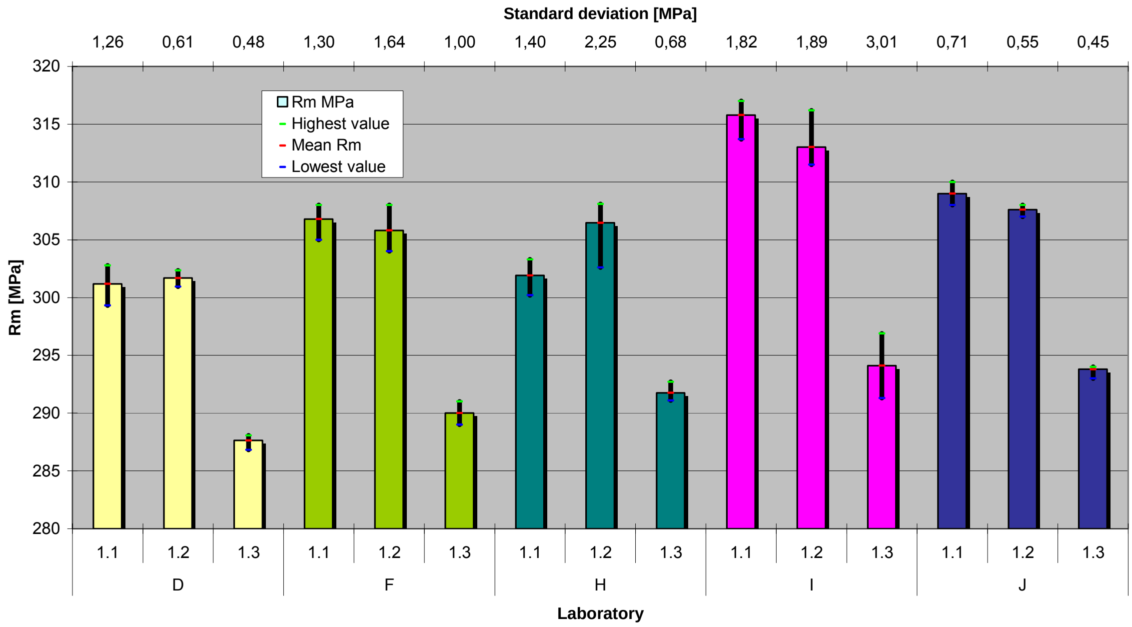


Figure 11: R_m for material DX56 with ISO 12.5x50 test pieces and extracted outliers

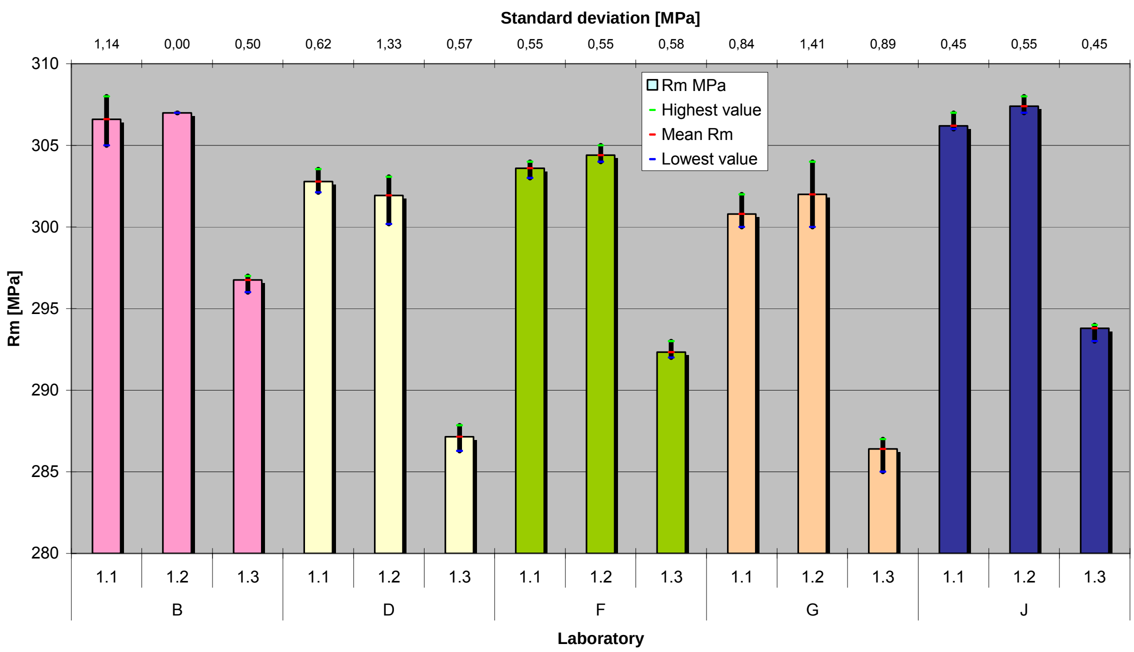


Figure 12: R_m for material DX56 with ISO 20x80 test pieces and extracted outliers

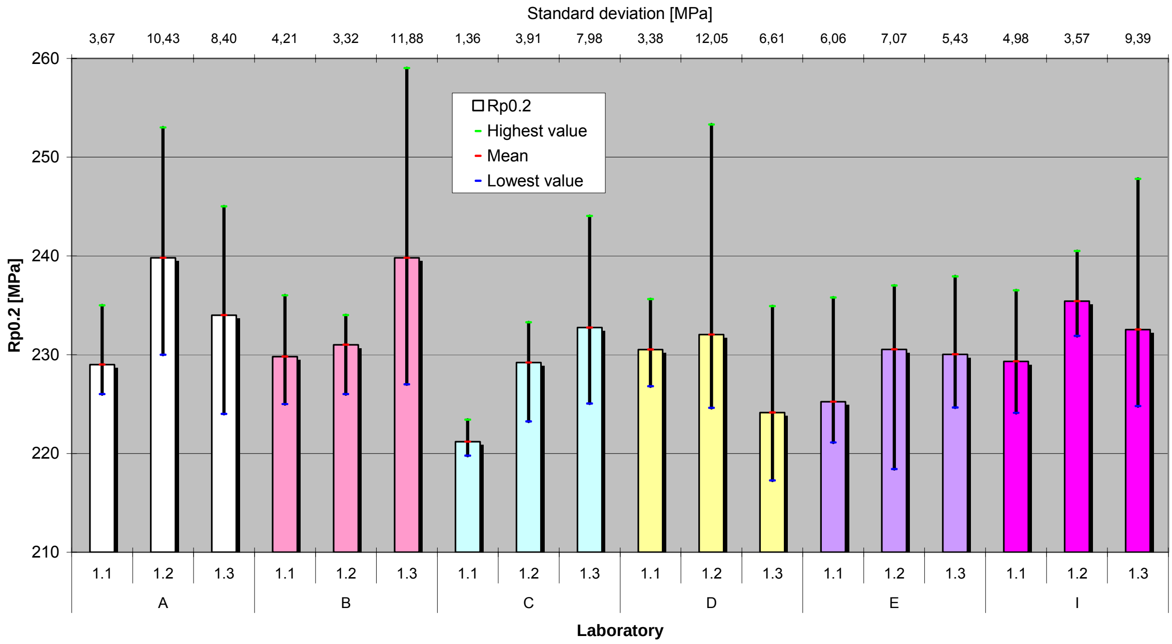


Figure 13: $R_{p0.2}$ for material 316L with test pieces M16-10x50 and extracted outliers

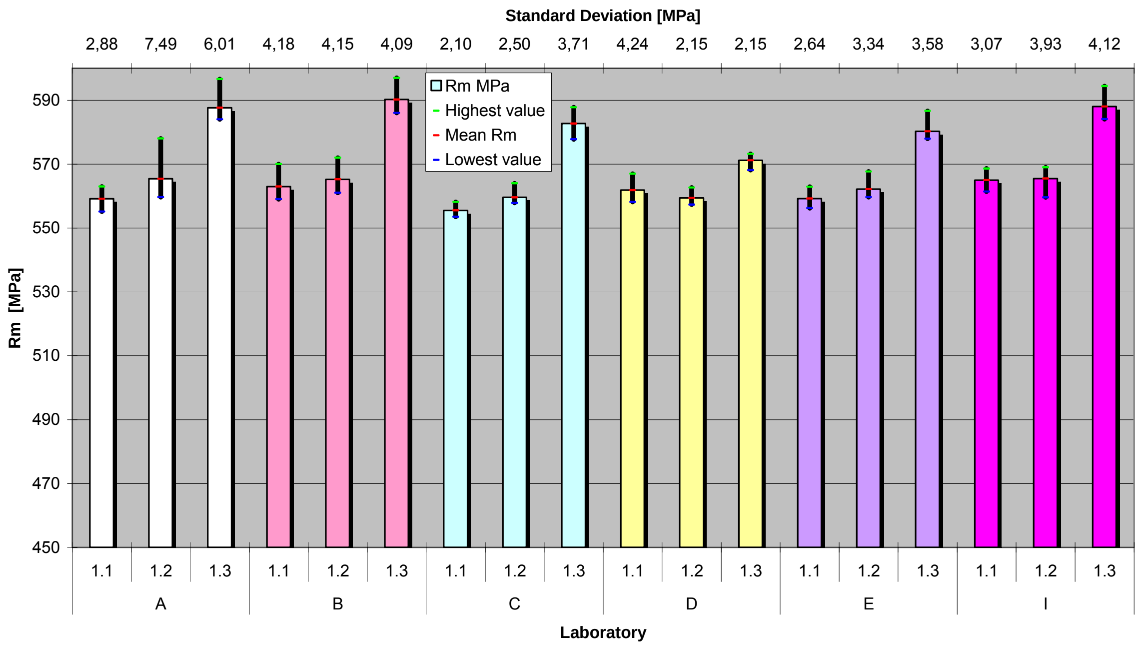


Figure 14: R_m for material 316L with test pieces M16-10x50 and extracted outliers

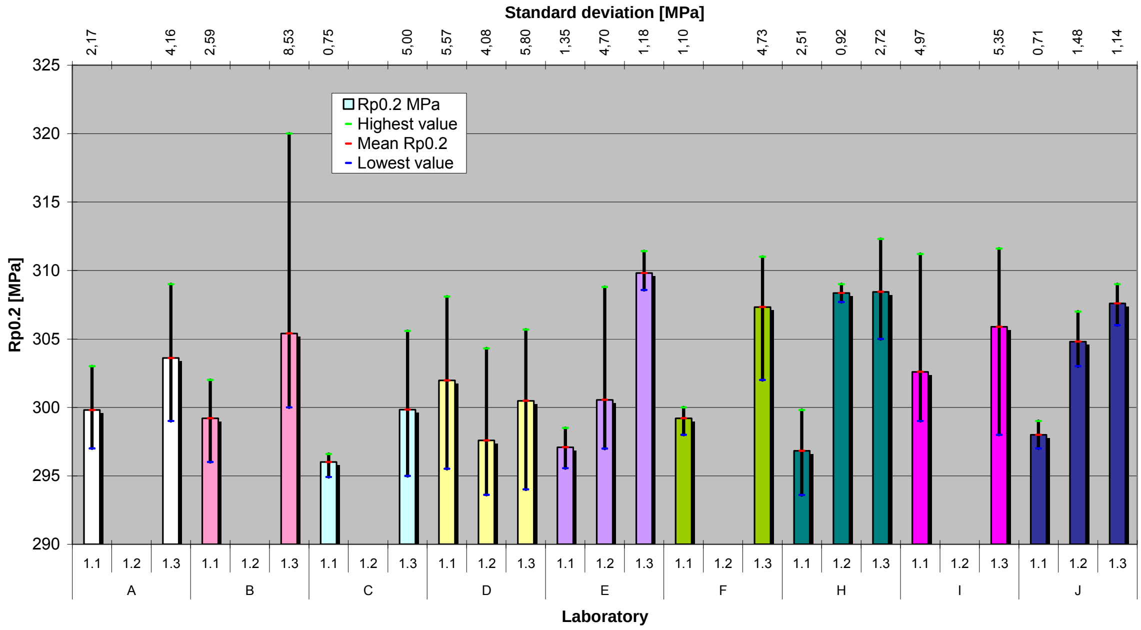


Figure 15: $R_{p0.2}$ for material Nimonic 75 with test pieces M14-10x50 and extracted outliers

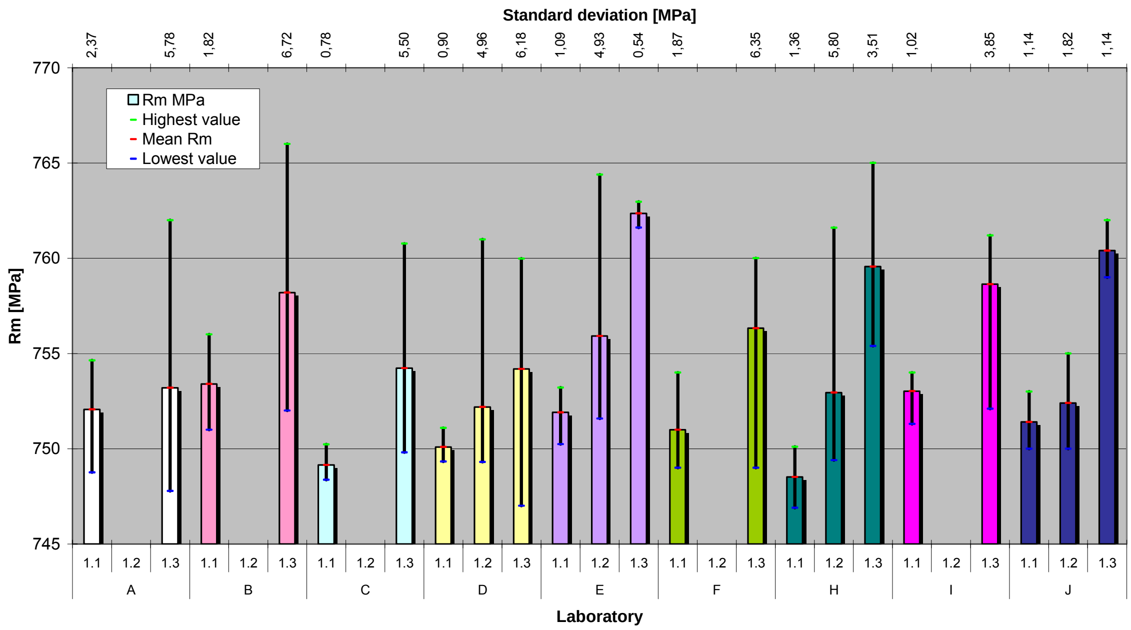


Figure 16: R_m for material Nimonic 75 with test pieces M14-10x50 and extracted outliers

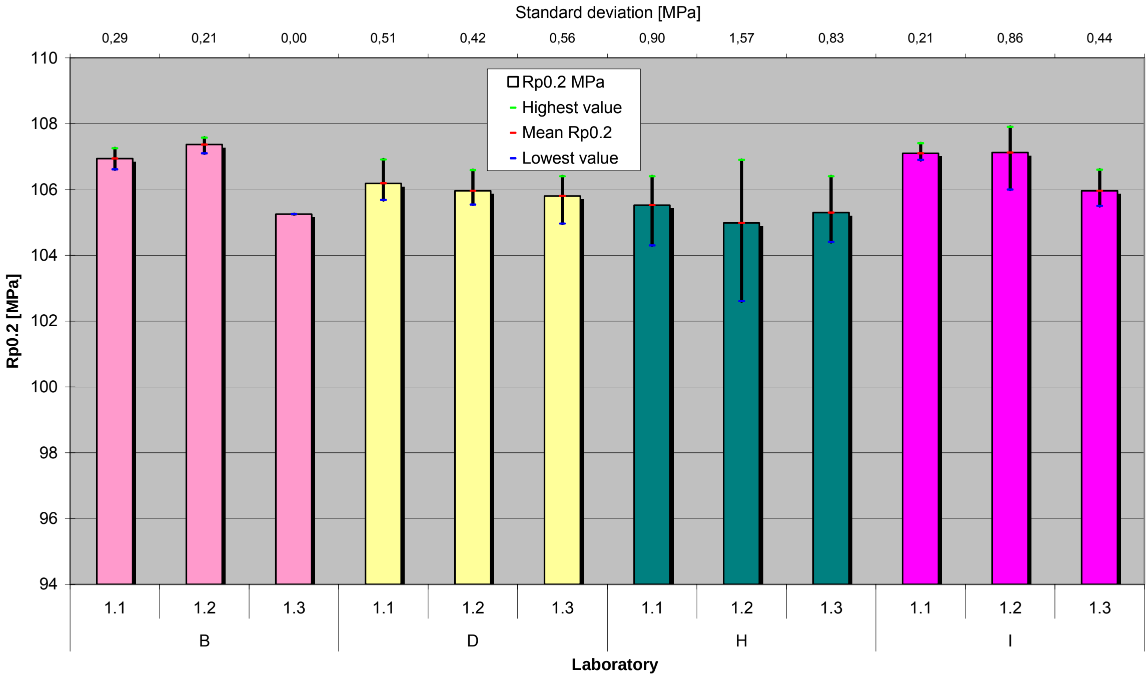


Figure 17: $R_{p0.2}$ for material AA5754 with test pieces ISO12.5x50 and extracted outliers

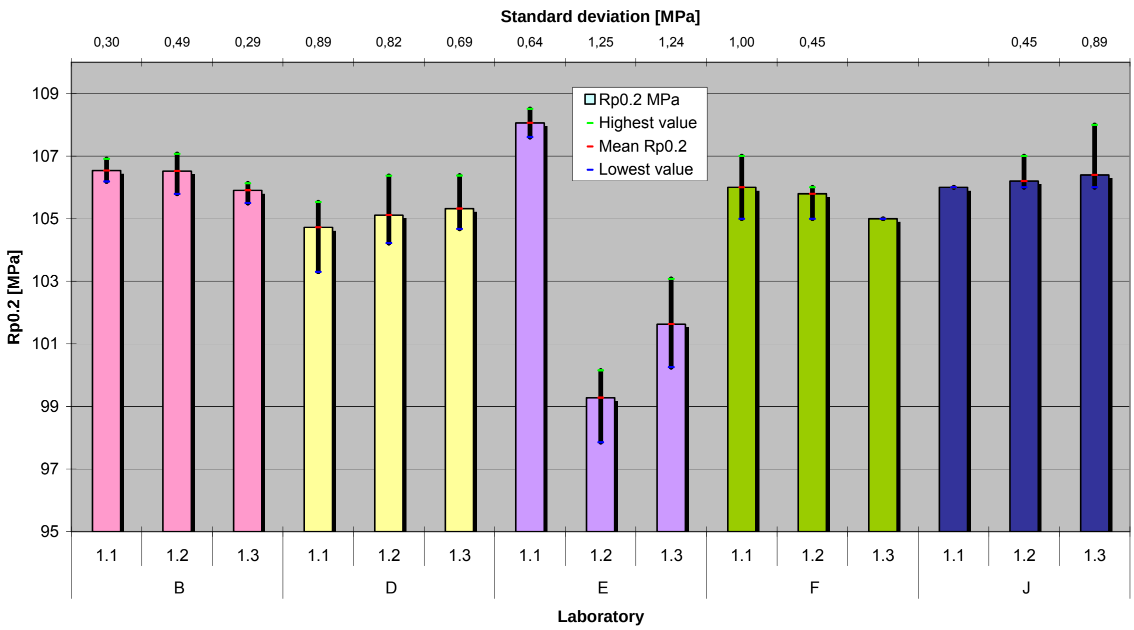


Figure 18: $R_{p0.2}$ for material AA5754 with test pieces ISO20x80 and extracted outliers

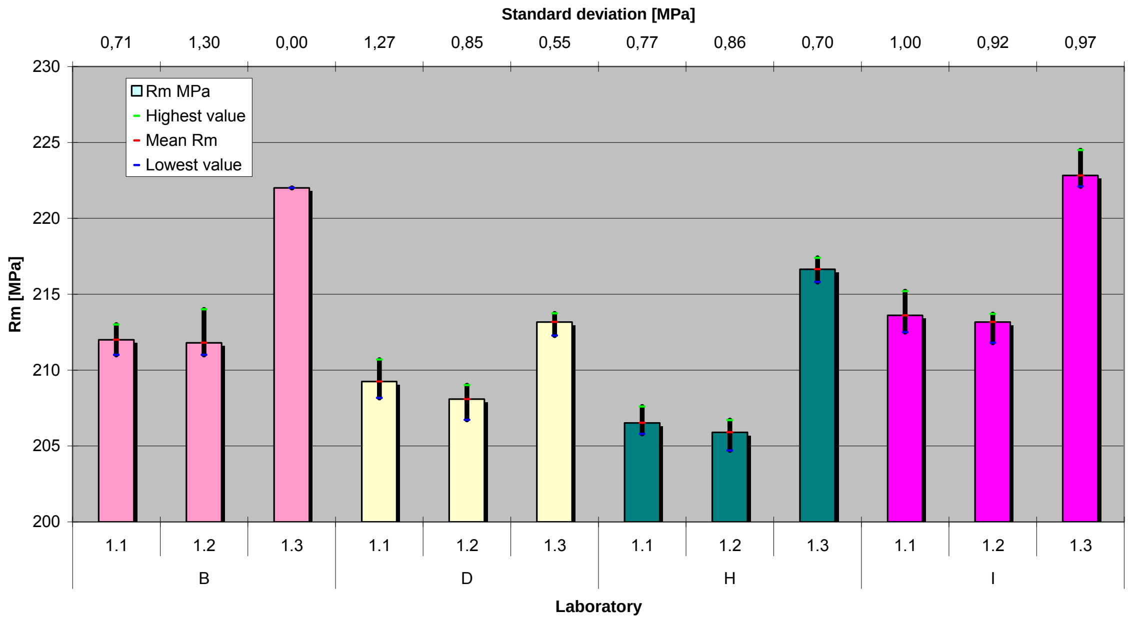


Figure 19: R_m for material AA5754 with test pieces ISO12.5x50 and extracted outliers

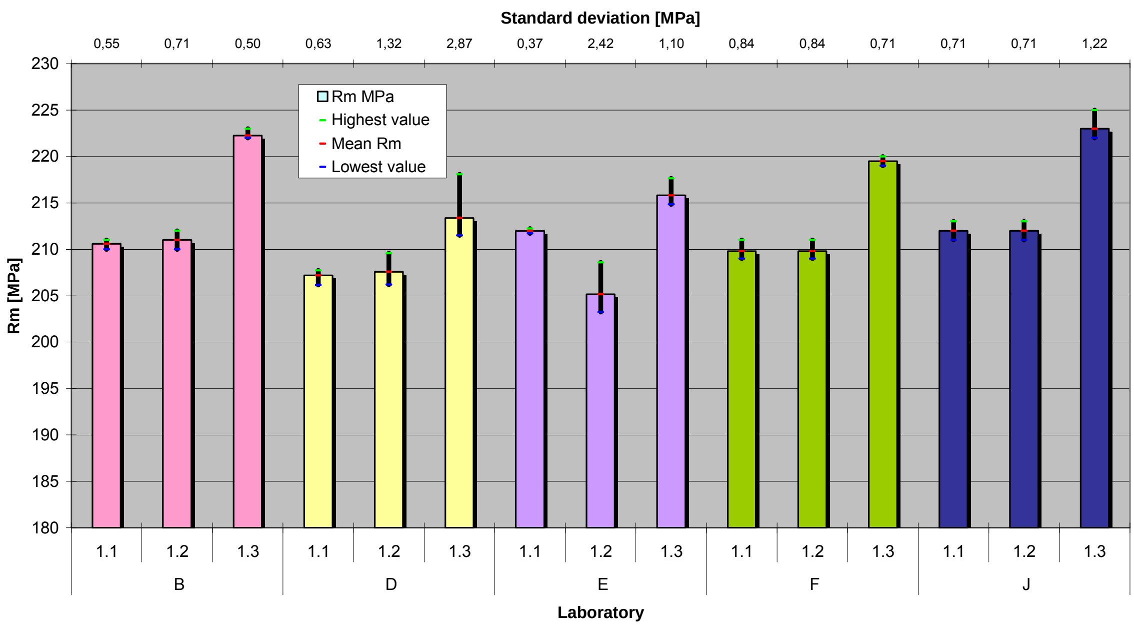


Figure 20: R_m for material AA5754 with test pieces ISO20x80 and extracted outliers

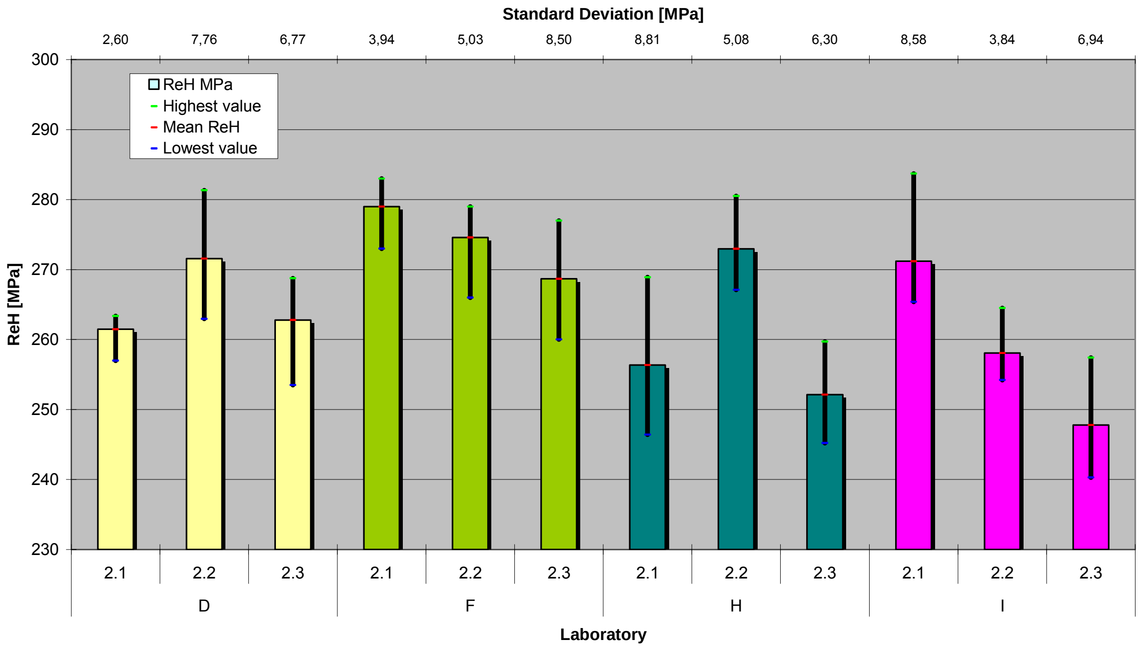


Figure 21: R_{eH} for material ZStE180 with test pieces ISO12.5x50 and extracted outliers

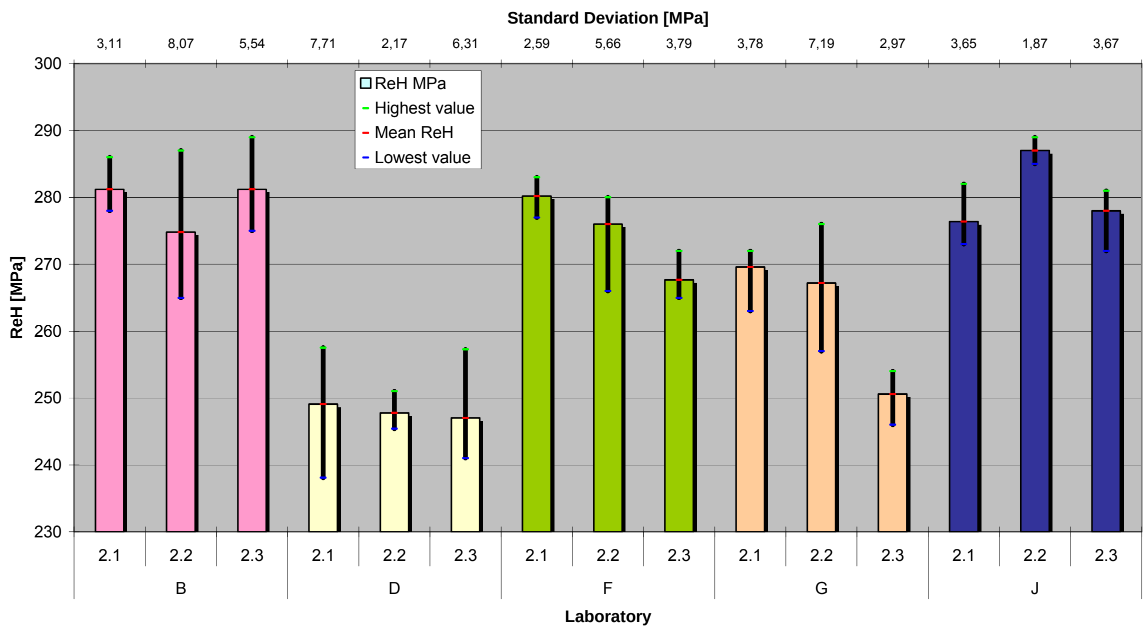


Figure 22: R_{eH} for material ZStE180 with test pieces ISO20x80 and extracted outliers

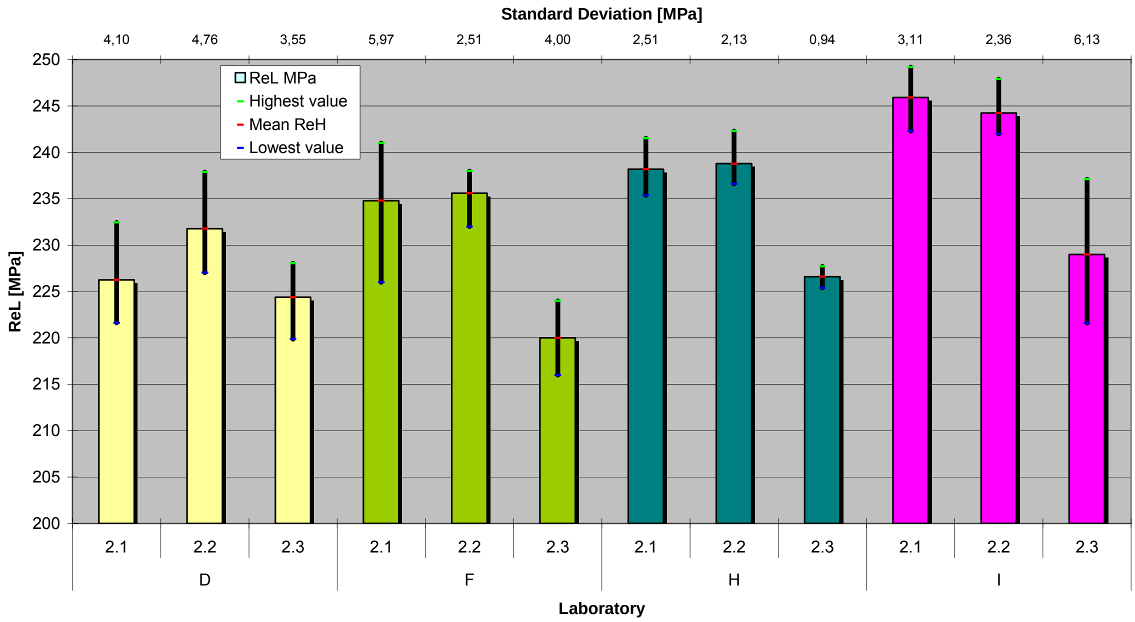


Figure 23: R_{eL} for material ZStE180 with test pieces ISO12.5x50 and extracted outliers

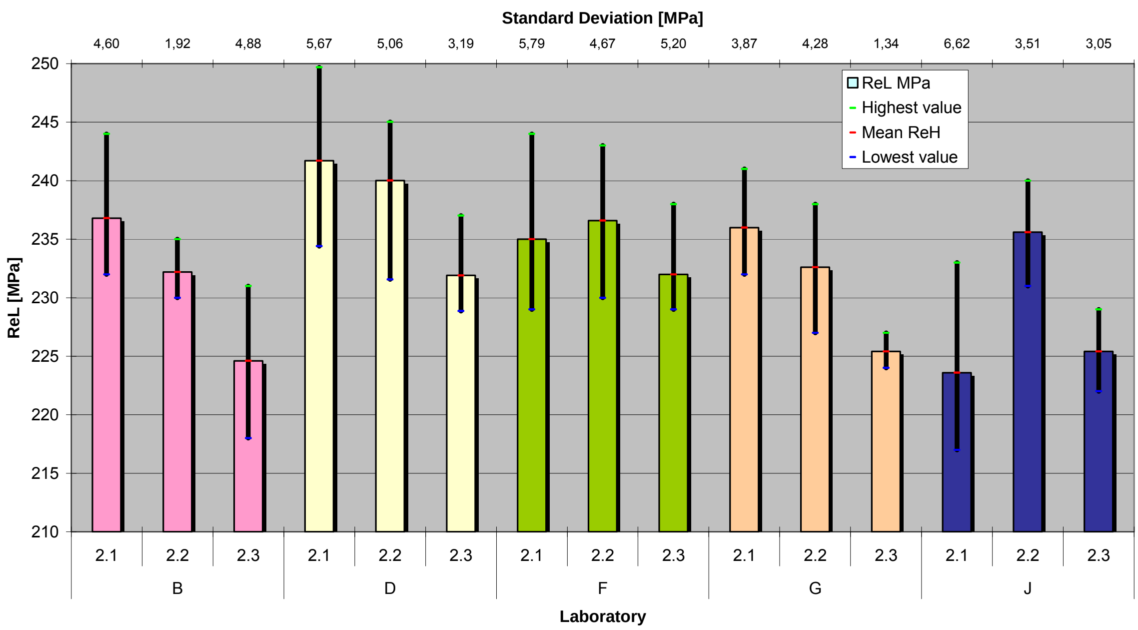


Figure 24: R_{eL} for material ZStE180 with test pieces ISO20x80 and extracted outliers

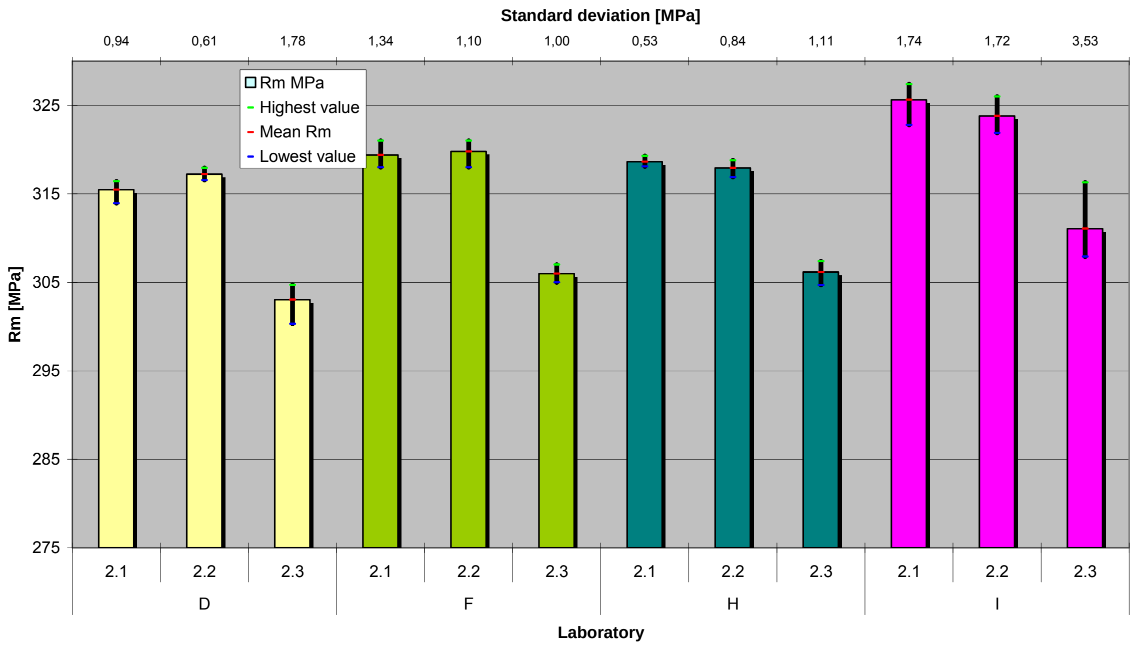


Figure 25: R_m for material ZStE180 with test pieces ISO12.5x50 and extracted outliers

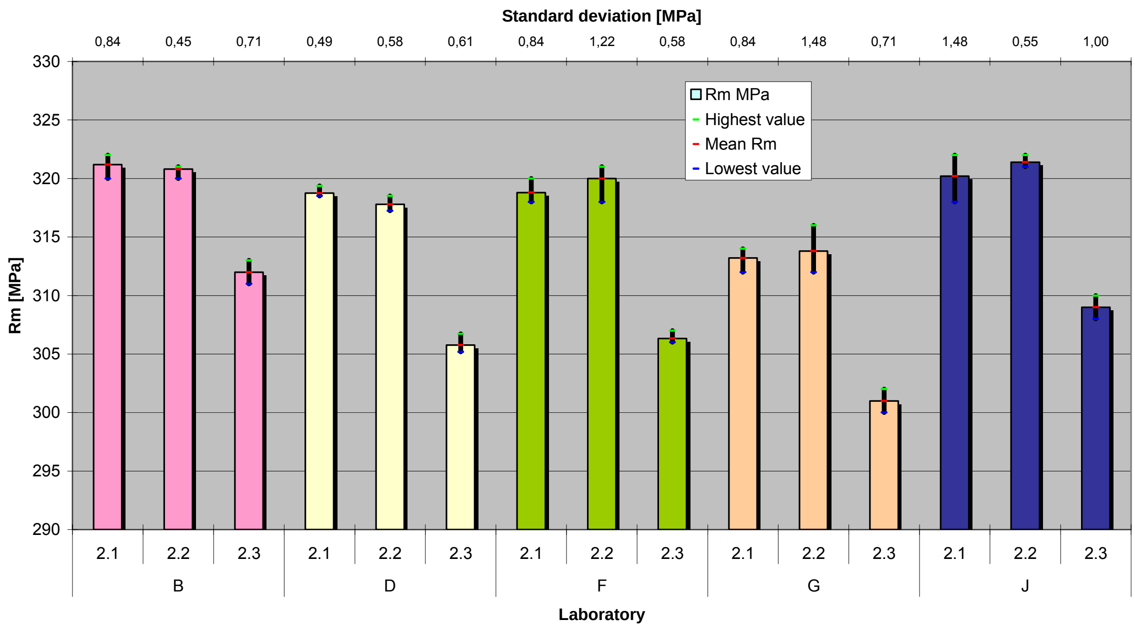


Figure 26: R_m for material ZStE180 with test pieces ISO20x80 and extracted outliers

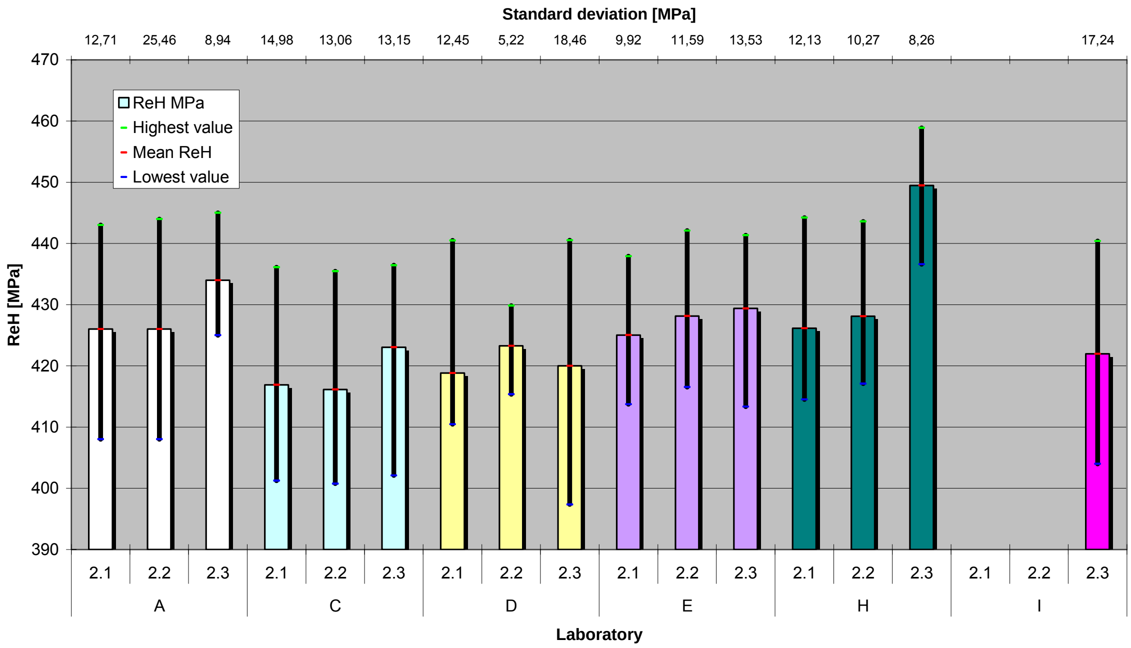


Figure 27: R_{eH} for material S355 with test pieces M16-10x50 and extracted outliers

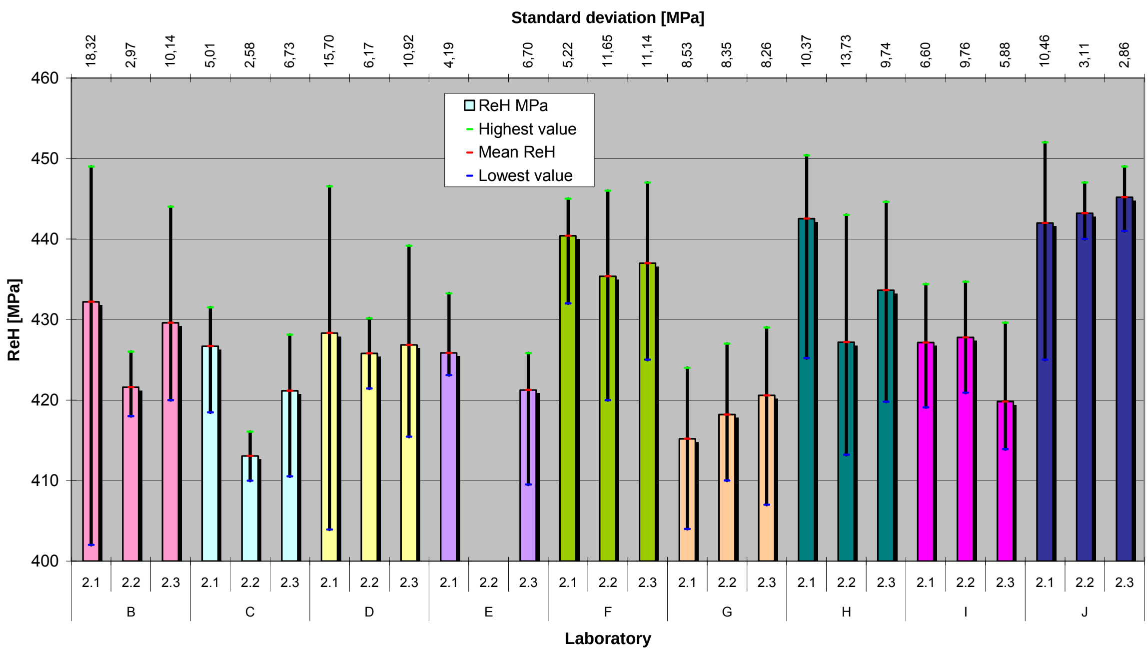


Figure 28: R_{eH} for material S355 with test pieces ISO12.5x50 and extracted outliers

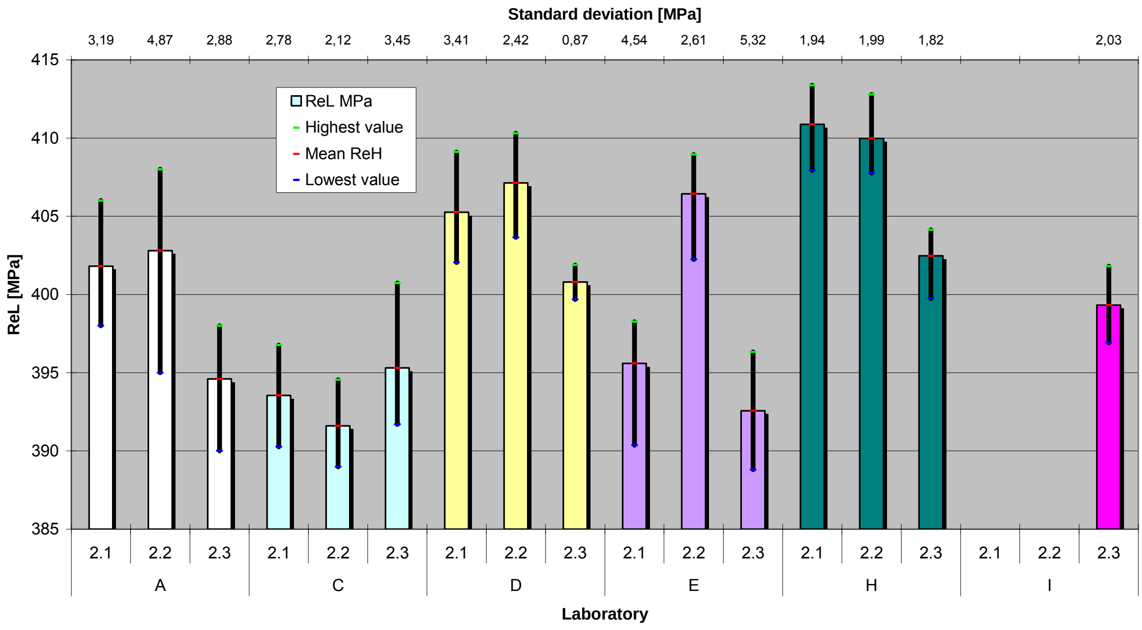


Figure 29: R_{eL} for material S355 with test pieces M16-10x50 and extracted outliers

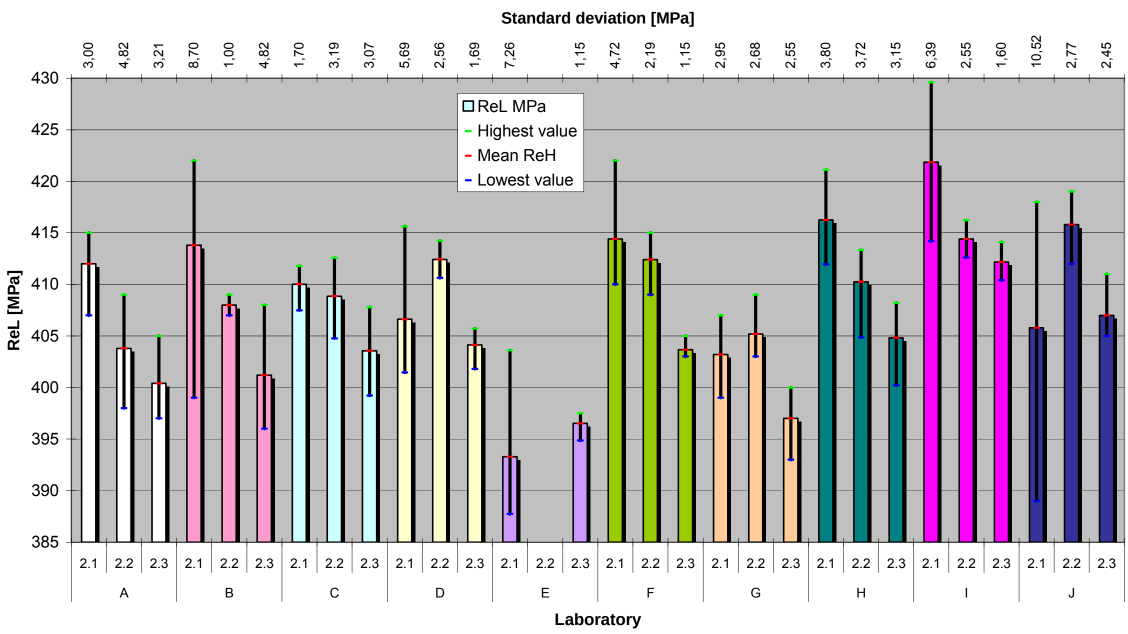


Figure 30: R_{eL} for material S355 with test pieces ISO12.5x50 and extracted outliers

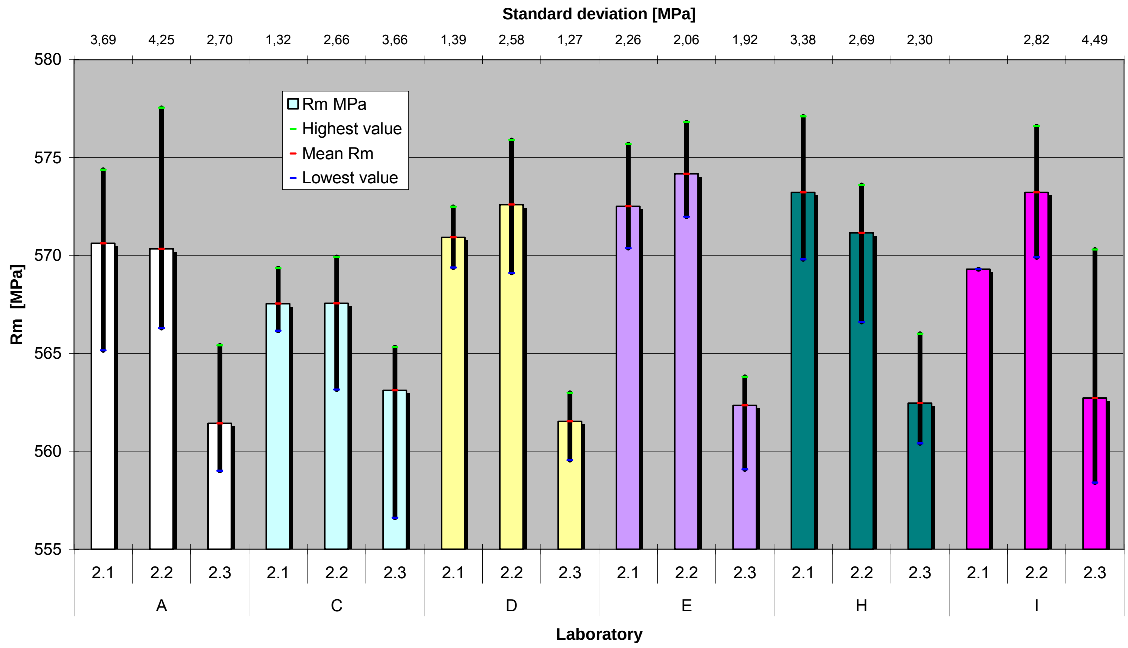


Figure 31: R_m for material S355 with test pieces M16-10x50 and extracted outliers

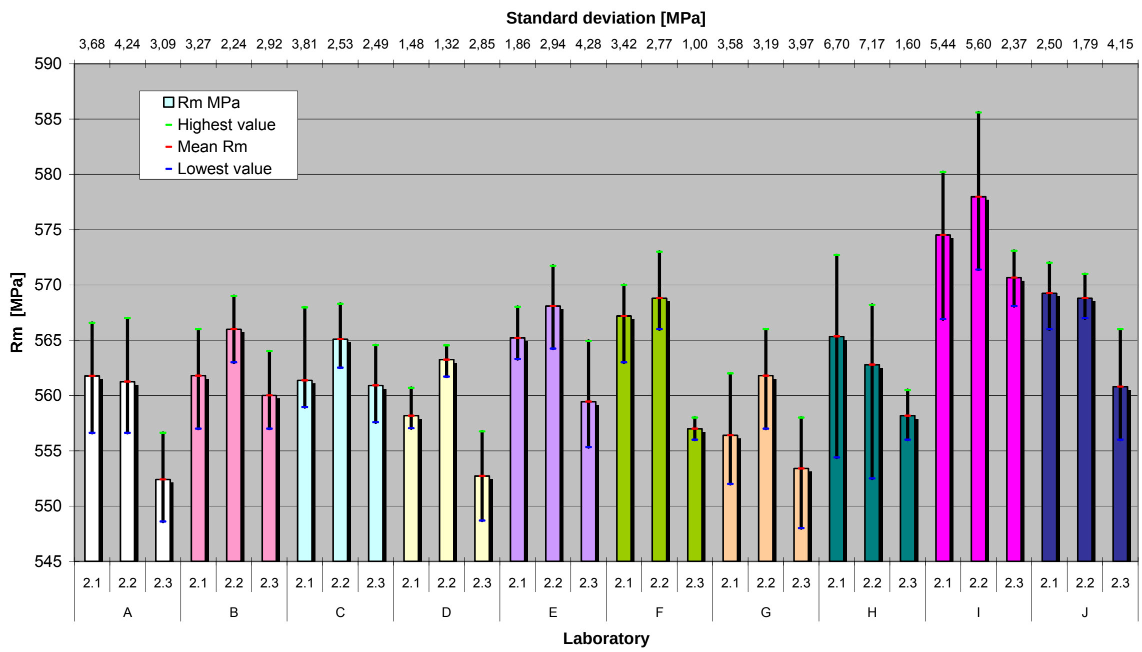


Figure 32: R_m for material S355 with test pieces ISO12.5x50 and extracted outliers

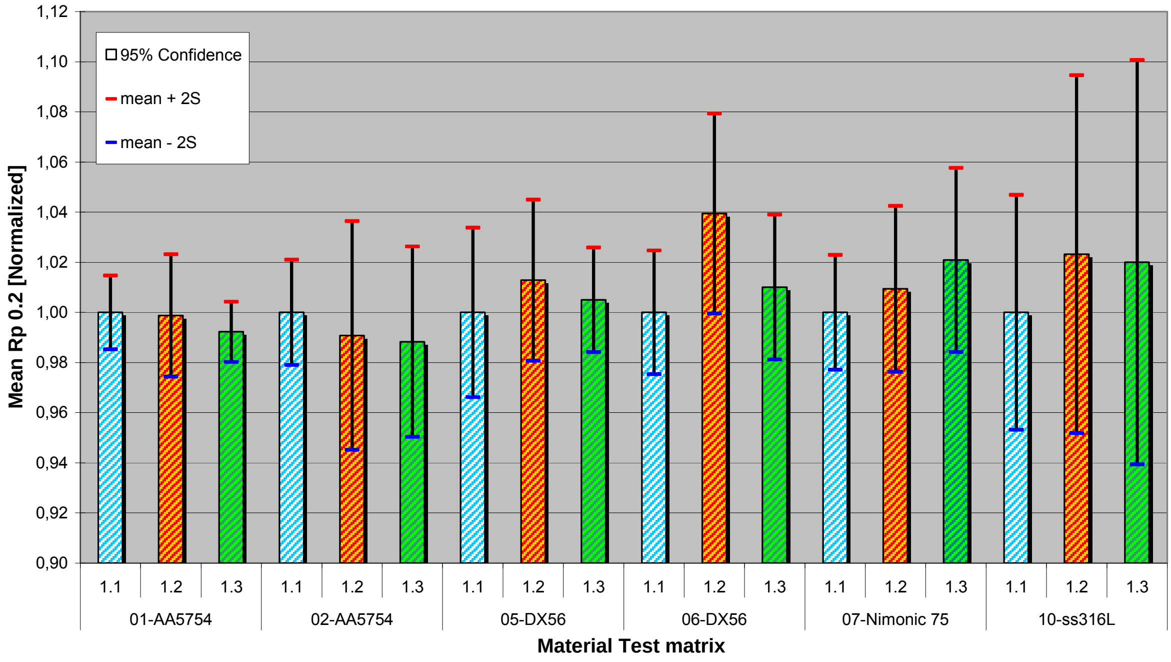


Figure 33: Normalised test results for $R_{p0.2}$ of the materials AA5754, DX56, Nimonic 75 and SS316L

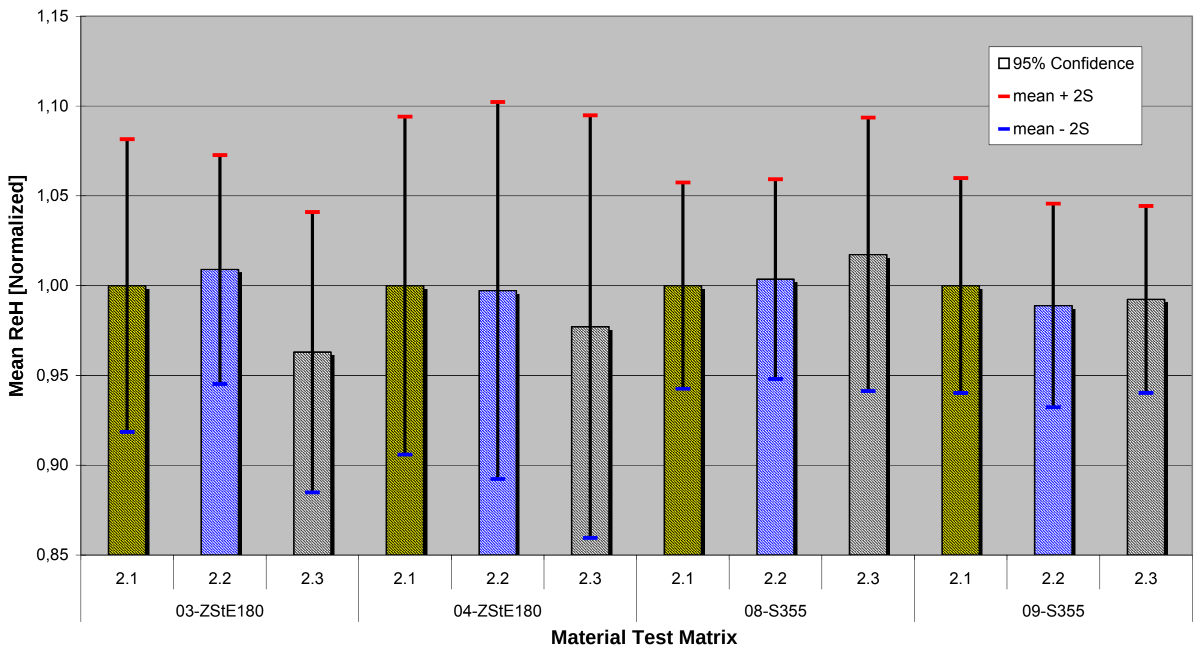


Figure 34: Normalised test results for R_{eH} of the materials ZStE180 and S355

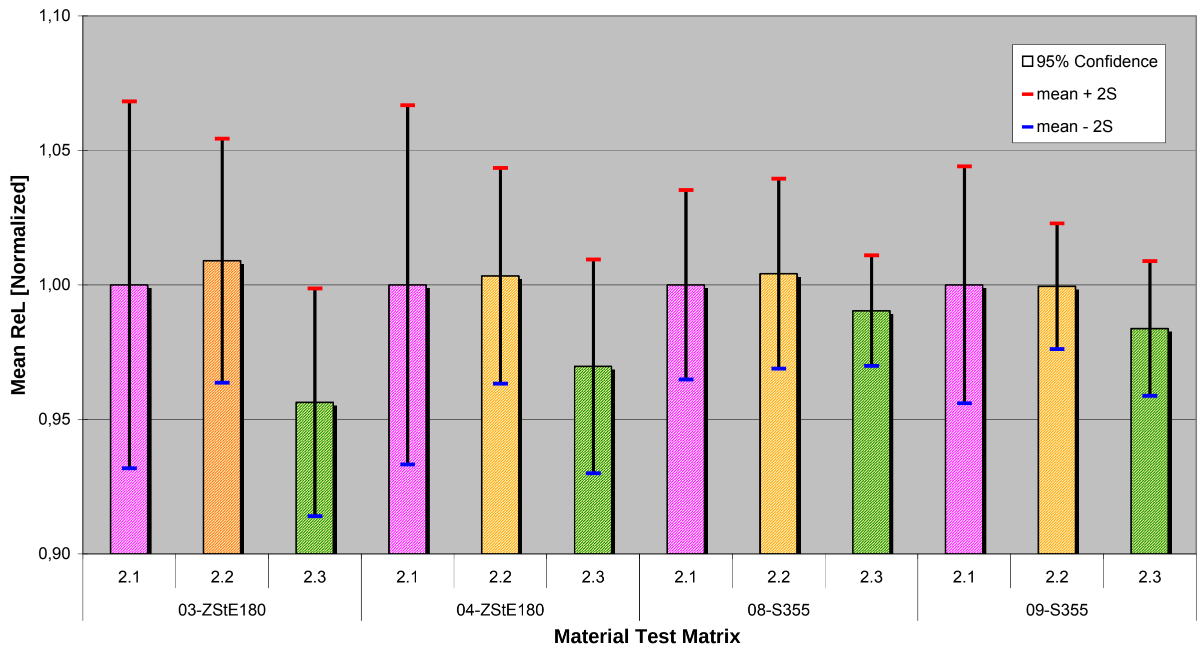


Figure 35: Normalised test results for R_{eL} of the materials ZStE180 and S355

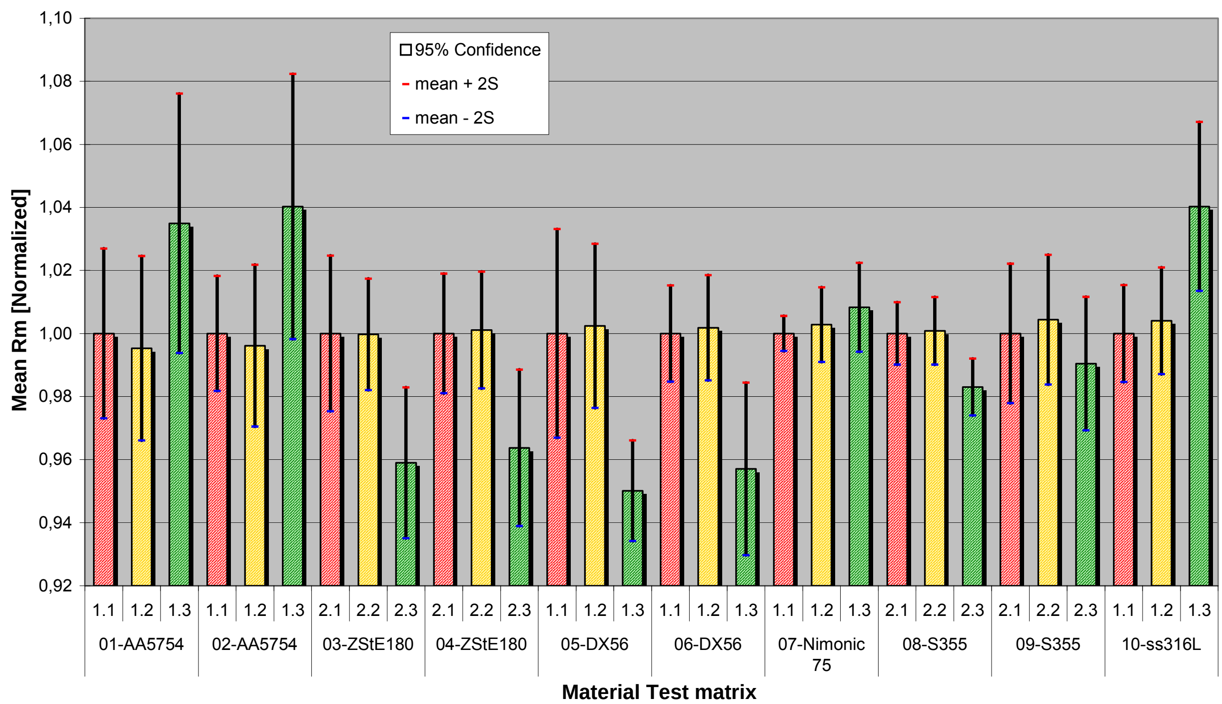


Figure 36: Normalised test results for R_m of the materials AA5754, ZStE180, DX56, Nimonic 75, S355 and SS316L

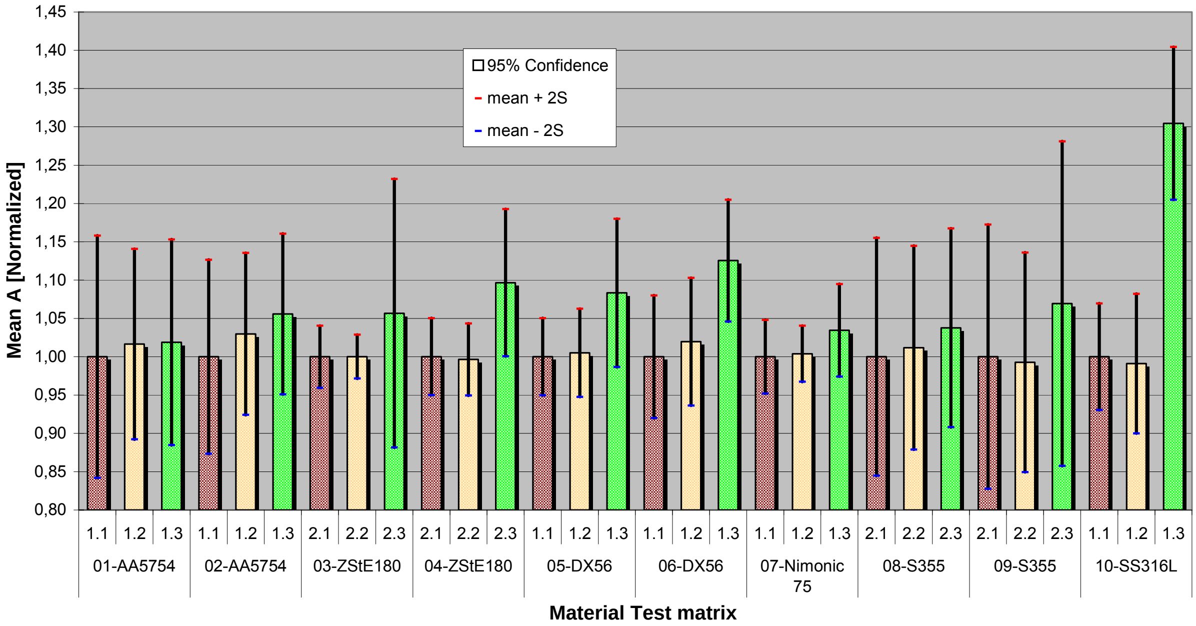


Figure 37: Normalised test results for A of the materials AA5754, ZStE180, DX56, Nimonic 75, S355 and SS316L

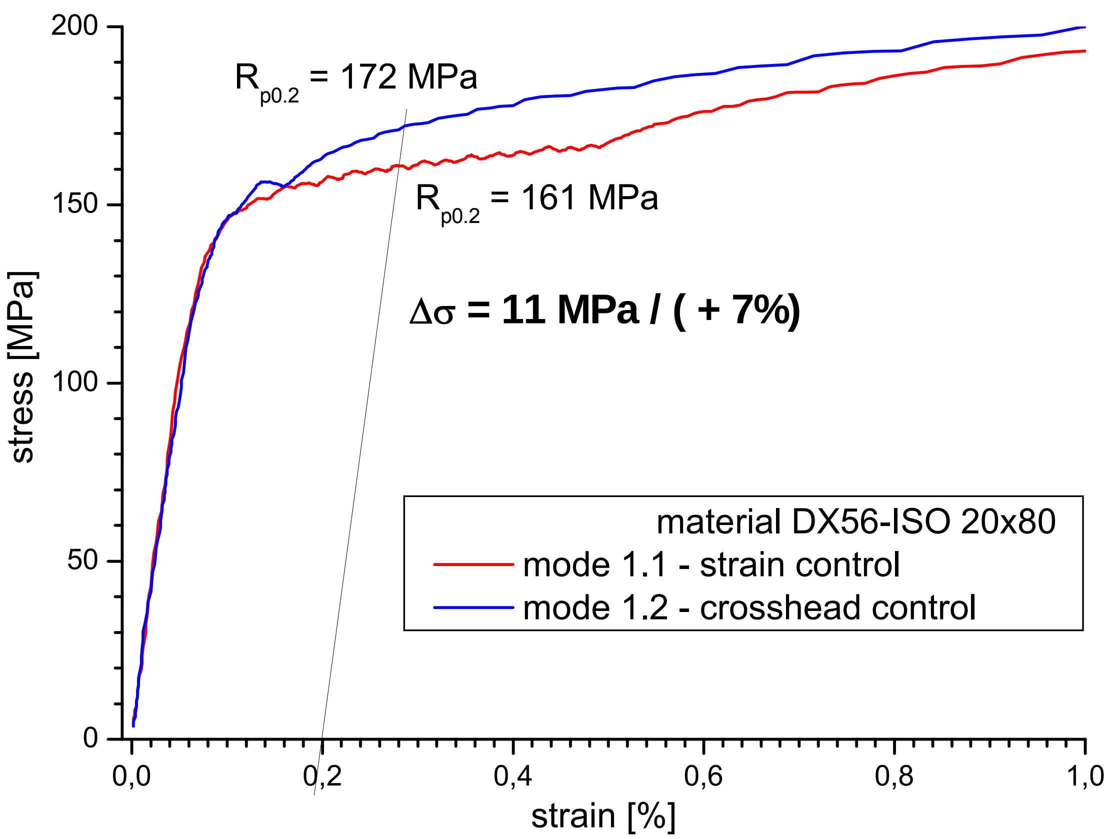
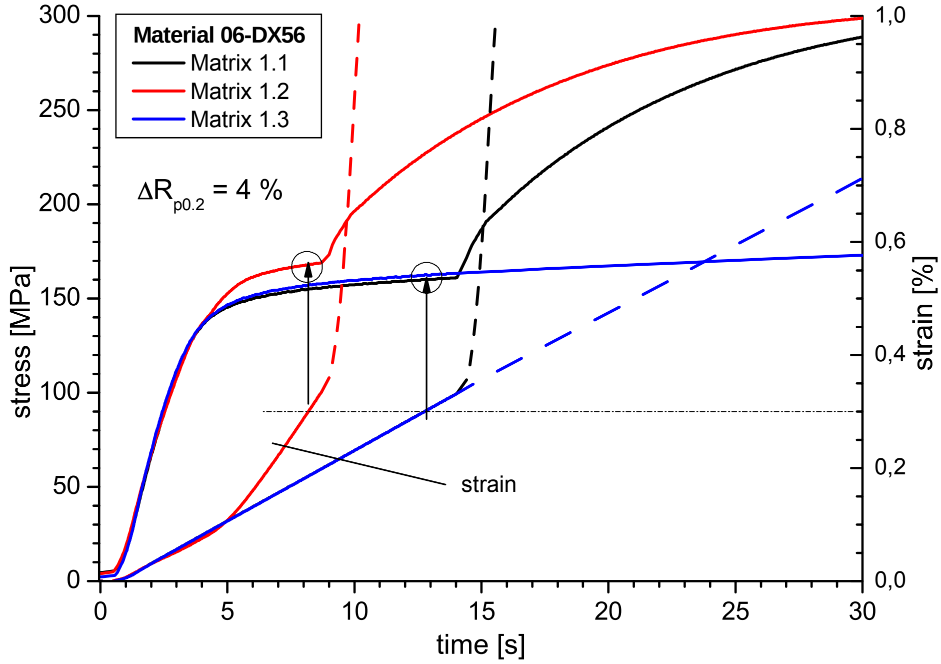


Figure 38: Stress strain curves until 1% strain for material DX56 with different values for $R_{p0.2}$ for different control modes



Matrix 1.2 with const. crosshead separation rate: $v_c = L_c \times \dot{\varepsilon}_{Lc}$

Figure 39: Stress and strain vs. time for the material DX56 (ISO 20x80) showing the influence of the control mode and testing speed on $R_{p0.2}$

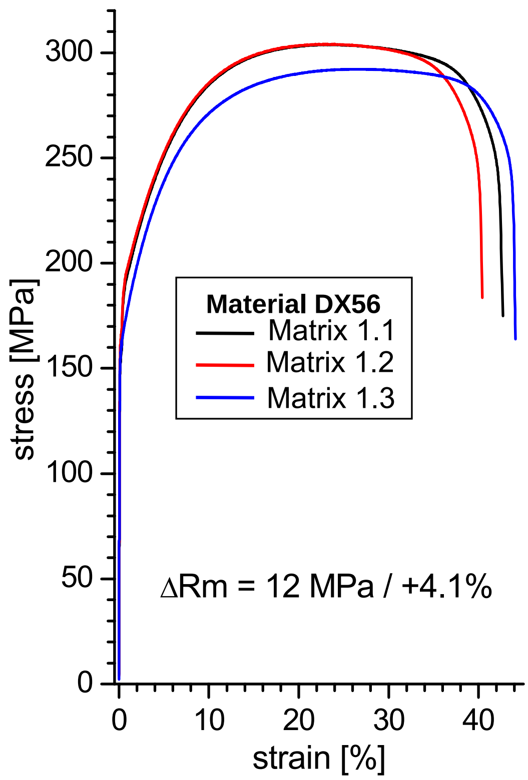


Figure 40: Stress strain curves for modes 1.1, 1.2, and 1.3 at the material DX56

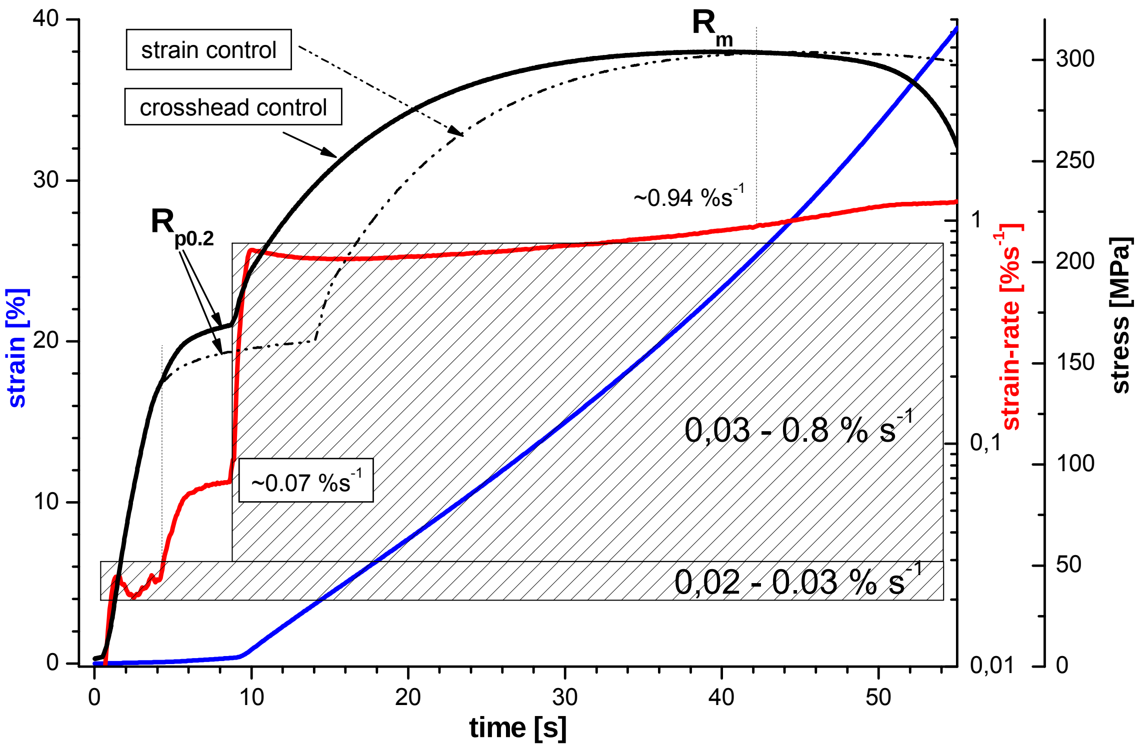


Figure 41: Stress, strain and strain rate vs. time for DX56 (ISO20x80) for modes 1.1 and 1.2 and the allowed testing speed

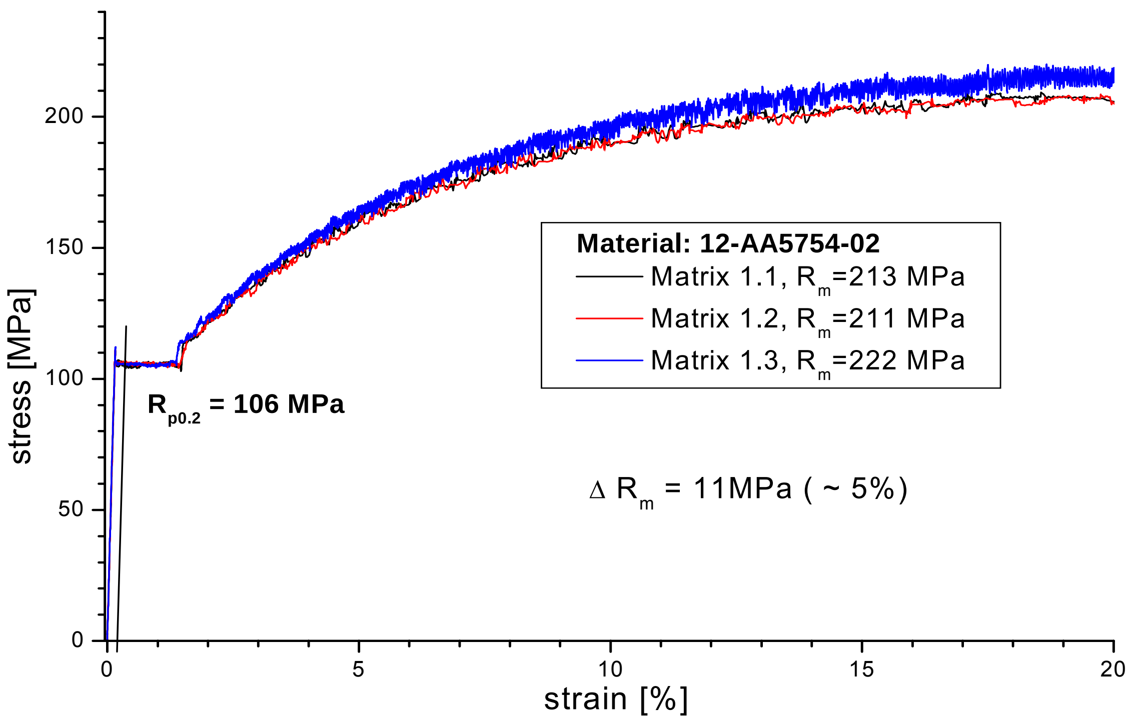


Figure 42: Stress strain curves for AA5754 (ISO20x80) for modes 1.1, 1.2 and 1.3

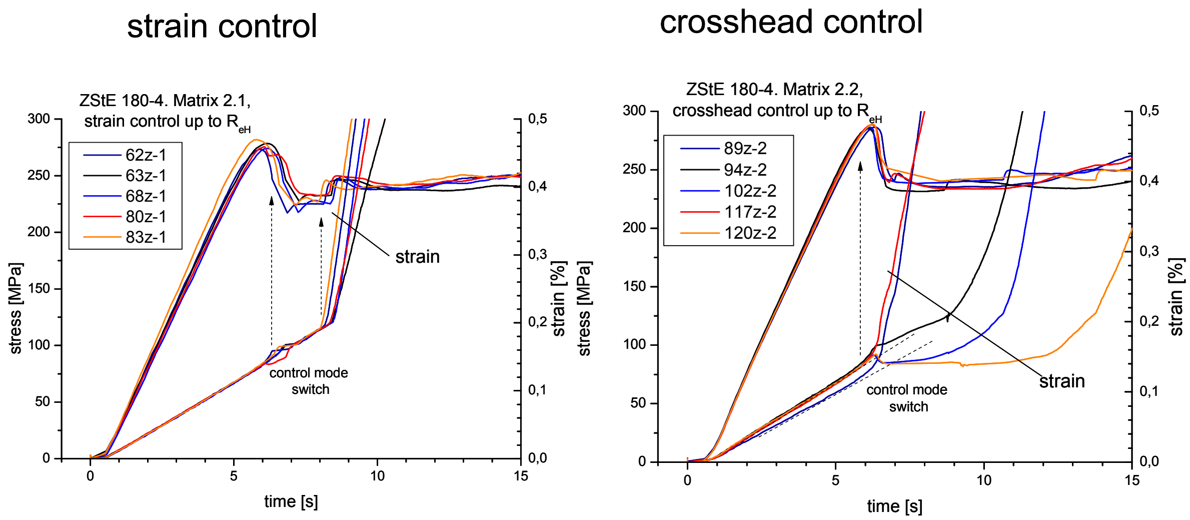


Figure 43: Stress, strain vs. time for ZStE180, mode 2.1 and 2.2

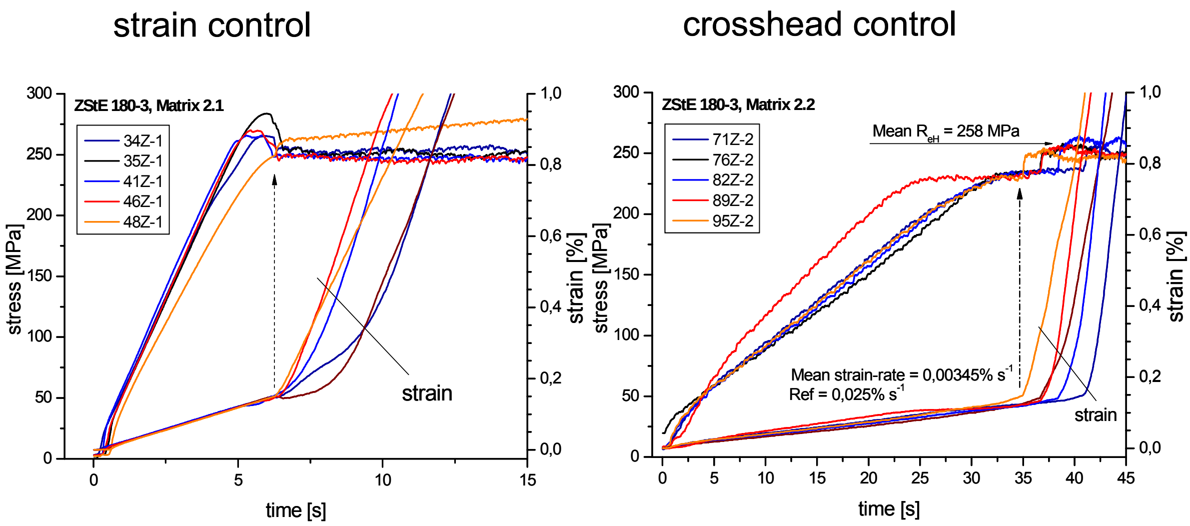


Figure 44: Stress, strain vs. time for ZStE180, mode 2.1 and 2.2

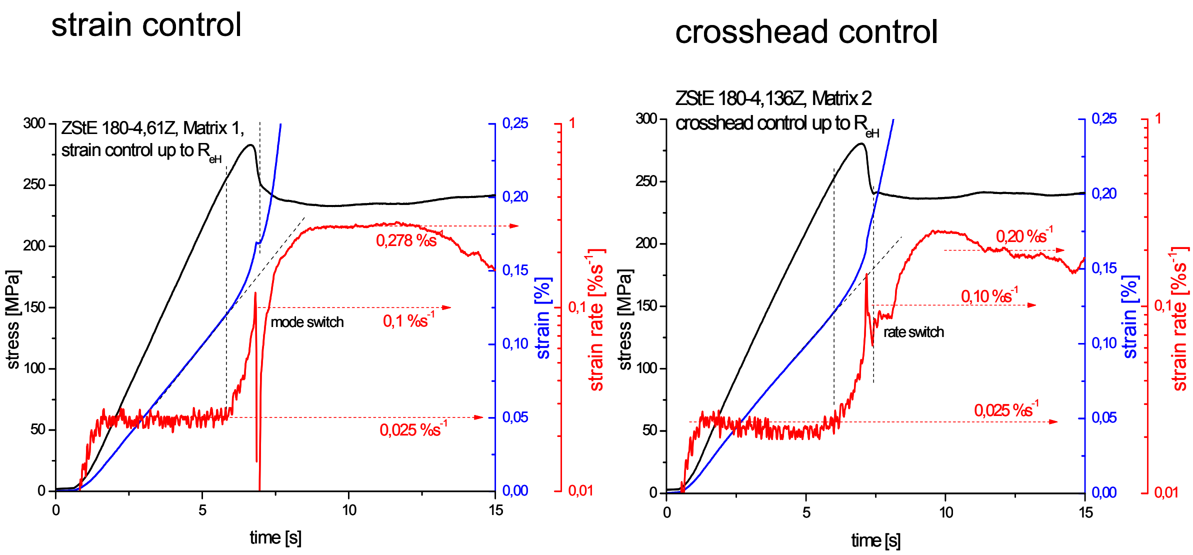


Figure 45: Stress, strain, strain rate vs. time for ZStE180, mode 2.1 and 2.2

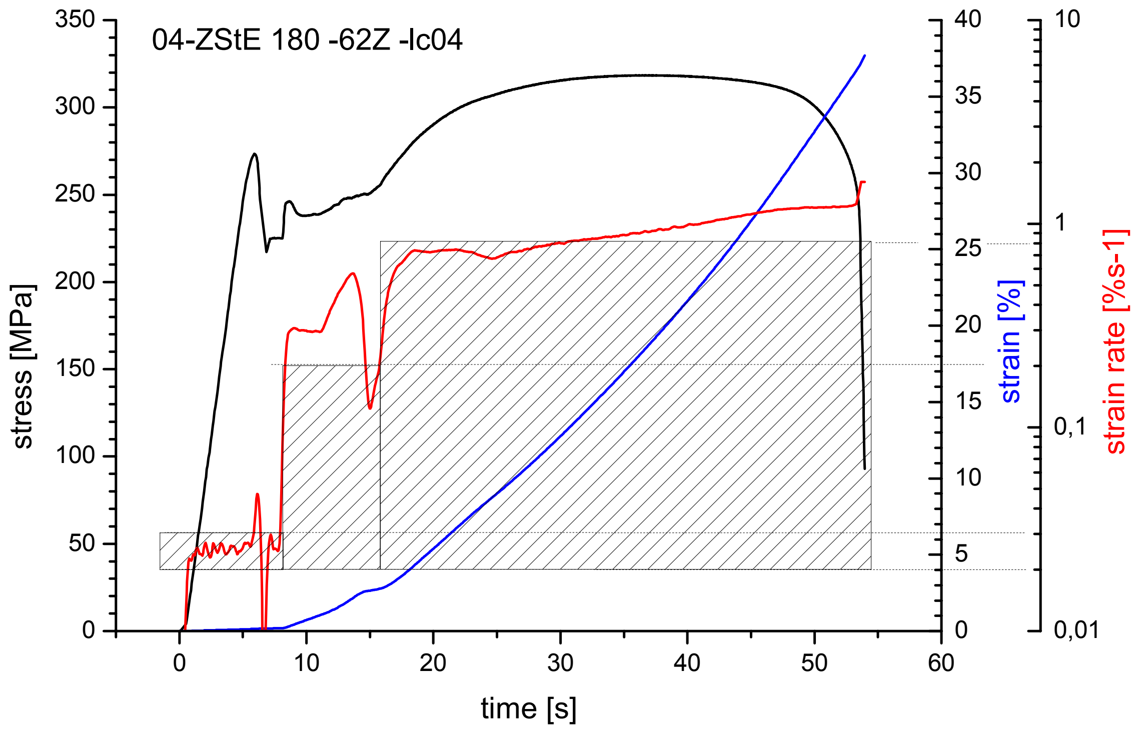


Figure 46: Stress, strain, strain rate for ZStE180, mode 2.1, allowed testing speed

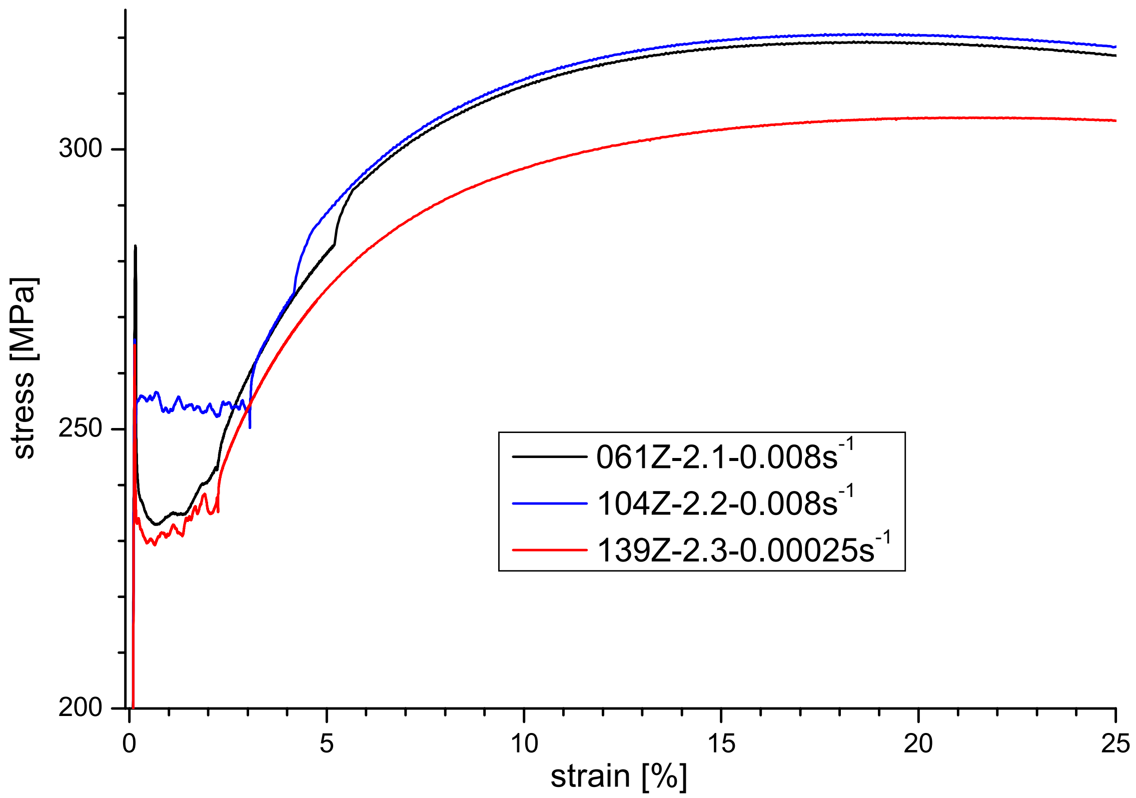


Figure 47: Stress strain curves for ZStE180, mode 2.1, 2.2, 2.3; influence of strain rate on R_m

ANNEX A

BAM V.21 Berlin, 11-Feb-03

TENSTAND WP4

Instructions for tensile round robin test program

Preface

For this program each participant has been allocated a code number as reference to all reports associated to this test program. The code of your laboratory will be registered on the test piece delivery list. All participants will receive such a list with the delivered test pieces, see annex 1 and a receipt form in order to trace the progress of the program.

All tests must be performed according to EN 10002 -1 : 2001.

There are special test programs for materials with 0.2% proof strength and such for materials with upper and lower yield strength, see annex 2, pos. 1.1-1.3 and pos. 2.1-2.3 .

All tests must be performed with an extensometer gauge length $L_e \geq L_o/2$.
Sampling frequency for data acquisition see EN 10002-1, annex A.

Deliverables to be sent to BAM after testing:

- All test pieces as broken pair with readable test piece number.
  - Results for each test piece report only in the prepared Excel sheets. Use the template file *"WP4_template_test_results.xls"* (S_0, Modulus, R_{eH}, R_{eL} or $R_{p0,2}$, R_m, A). See annex 3 .
- Determination of percentage elongation after fracture (A):
  - manually determined with marking method (mandatory)
  - determination computer controlled with extensometer at the test piece until fracture (optional)
  - ASCII raw data file for each test including a header and a data section. Data section with values for time, displacement (position/crosshead), strain and force according to the Tenstand data file format of Work Package 2, see annex 4. A working template is available with the file *"WP4-template_raw_data.txt".*

Redelivery of all results in computer readable form like CD-ROM (recommended), diskettes or e-mail attachment. For properly and efficient analysis all participants are asked to consider above points. Testing should be carried out as soon as possible after receiving the test pieces and results reported within eight weeks (end of April 2003).

Receipt form and completed results send to:
Bundesanstalt für Materialforschung und -prüfung (BAM)
Labor V.21
S. Ledworuski
Unter den Eichen 87
D-12205 Berlin
Phone: ++49 30 8104 3132, Fax: ++49 30 8104 1527
e-mail: siegmar.ledworuski@bam.de

Annex 1

Tenstand: Test piece delivery list

TENSTAND: Testpieces according to WP4

Delivery list for: nn - code of laboratory: xx

ref. no.	material	test piece shape	test piece name				total number of testpieces
			test program			pieces for pretests	
			1.1 / 2.1	1.2 / 2.2	1.3 / 2.3		
1	AA5754		… , … , … , … , …				
2							
3	ZStE 180 *)						
4							
5	DX 56						
6							
7	NiCr20Ti						
8	S355 *)						
9							
10	stainless steel 316L						
	Total						

*) material with upper and lower yield strength according to WP4 - Test matrix for tensile test program 2.1–2.3 (Annex 2)

Annex 2

WP4 - Test matrix for tensile test program

1. Test program for materials with 0.2%-proof strength

1.1 **strain control** 0.00025 s^{-1} strain rate and determination of $R_{p0.2}$, then displacement control at equivalent 0.008 s^{-1} strain-rate to failure and determination of R_m (EN 10002 new proposal).

1.2 **displacement control** (crosshead) equivalent 0.00025 s^{-1} strain rate in elastic range and determination of $R_{p0.2}$ then displacement control at equivalent 0.008 s^{-1} strain rate to failure and determination of R_m (EN 10002-1:2001)

1.3 **strain control** 0.00025 s^{-1} strain rate and determination of $R_{p0.2}$, then displacement control at equivalent 0.00025 s^{-1} strain-rate until failure and determination of R_m.

2. Test program for materials with upper and lower yield strength

2.1 **strain control** 0.00025 s^{-1} strain rate up to R_{eH}, then displacement control at equivalent 0.002 s^{-1} strain rate up to end of yield and determination of R_{eL}, then displacement control at equivalent 0.008 s^{-1} strain rate to failure and determination of R_m.

2.2 **displacement control** equivalent 0.00025 s^{-1} strain rate up to R_{eH} then displacement control at equivalent 0.002 s^{-1} until end of yield and determination of lower yield R_{eL}, then displacement control at equivalent 0.008 s^{-1} strain rate to failure and determination of R_m.

2.3 **strain control** 0.00025 s^{-1} strain rate up to R_{eH}, then displacement control at equivalent 0.00025 s^{-1} strain rate up to failure and determination of R_{eL} and R_m.

Note: The test program was developed and agreed on the 3rd Tenstand meeting in Florange, France in February 2002.

Annex 3

Prepared Excel sheets for test results - *“WP4-template_test_results.xls”*

TENSTAND WP4: results - test program 1.1 - 1.3 for materials with proof strength

code of laboratory: **ref. no.:** **material:** **shape:** **date:**

	test piece name	thickness or diameter (of the parallel length)	width (of the parallel length)	orginal cross-sectional area (of the parallel length)	modulus of elasticity	proof strength	tensile strength	extensometer gauge length	final gauge length after fracture	percentage elongation after fracture: manual	percentage elongation after fracture: computer controlled
		a / d	b	S_0	E	$R_{p0.2}$	R_m	L_e	L_u	A / A_{80mm} / A_{50mm}	
		[mm]	[mm]	[mm²]	[GPa]	[MPa]	[MPa]	[mm]	[mm]	[%]	[%]
test program 1.1 strain control											
test program 1.2 displacement control											
test program 1.3 strain control											

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TENSTAND WP4: results - test program 2.1 - 2.3 for materials with upper and lower yield

code of laboratory: **ref. no.:** **material:** **shape:** **date:**

	test piece name	thickness or diameter (of the parallel length)	width (of the parallel length)	orginal cross-sectional area (of the parallel length)	modulus of elasticity	upper yield strength	lower yield strength	tensile strength	extensometer gauge length	final gauge length after fracture	percentage elongation after fracture: manual	percentage elongation after fracture: computer controlled
		a / d	b	S_0	E	R_{eH}	R_{eL}	R_m	L_e	L_u	A / A_{80mm} / A_{50mm}	
		[mm]	[mm]	[mm²]	[GPa]	[MPa]	[MPa]	[MPa]	[mm]	[mm]	[%]	%
test program 2.1 strain control												
test program 2.2 displacement control												
test program 2.3 strain control												

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Annex 4

Example: TENSTAND DATA FILE - WP4-Testmatrix

```
"Test Laboratory Code:";"01"
"Date of test [mm.dd.yyyy]:";"01.15.02"
"Test material:";"Zst180 E"
"Specimen identification:";"15Z"
"Reference standard:";"EN 10002-1"
"Test temperature:";22;"deg C"
"Test machine [Type,load range]:";"Instron 8500, 100 kN"
"Software machine controll:";"Instron Merlin"
.
.
.
"Specimen geometry [round]/[rectangular]:";" rectangular "
"Cross-sectional area So:";15.81;"mm2"
"Extensometer gauge length Le:";80;"mm"
"Extensometer output [mm]/[mm/mm]/[%]:";"%"
"Parallel length Lc:";120;"mm"
"Remark 1:";"strain control, Tenstand test-matrix, program 1.1"
.
.
.
"time";"displacement";"strain";"force"
"s";"mm";"%";"kN"
0.000;0;0.000135428;0.04232992
0.500;0.04796;0.01119407;0.4942749
1.000;0.10184;0.02869719;1.213265
2.000;0.20384;0.05934288;2.459289
3.000;0.31384;0.08918928;3.660115
4.000;0.43492;0.1196606;4.778381
5.000;0.58372;0.1457821;5.113196
.
.
.
70.018;37.7332;-0.05611122;5.750359
72.518;40.13332;-0.05616256;5.158128
73.018;40.6132;-0.05614419;4.867177
73.518;41.0932;-0.05617828;2.30303
73.578;41.15092;-0.0561729;0.07541711
```

Note: In this data file the term ”displacement” has the same meaning as ”crosshead ”or ”position”. This give comparability for this term between electro-mechanical and hydraulic test machines.