# Fatigue properties of railway axles: new results of full-scale specimens

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TC24 Meeting – Advances in: *“Axle Durability Analysis and Maintenance”*

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# Summary

- *A common procedure to test full scale axles in order to achieve comparable results*
- *Axle body fatigue limit of standard materials (average value and standard deviation)*
- *Effect of surface corrosion when axles are in service without coating*
- *Effect of specific surface finishing that improves coating adhesion*
- *Effect of typical grove geometries used in powered axles*
- *Stress concentration profile along axle transitions and validation of FEM numerical models*
- *Press-fitted seats fretting-fatigue limit of standard materials (average value and standard deviation)*
- *Identification of possible changes to the European Standards*

# WP3 partners and their role

Manufacturing of testing components

Laboratories

Manufacturers

GHH

Valdunes

Bonatrans

CAF

Lucchini RS

Rafil

Railways

DB

SNCF

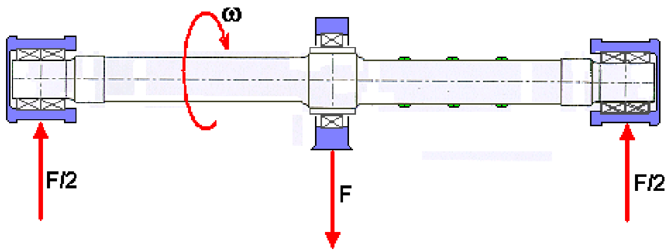
University and Research centers

Polimi

IWM-Fraunofer

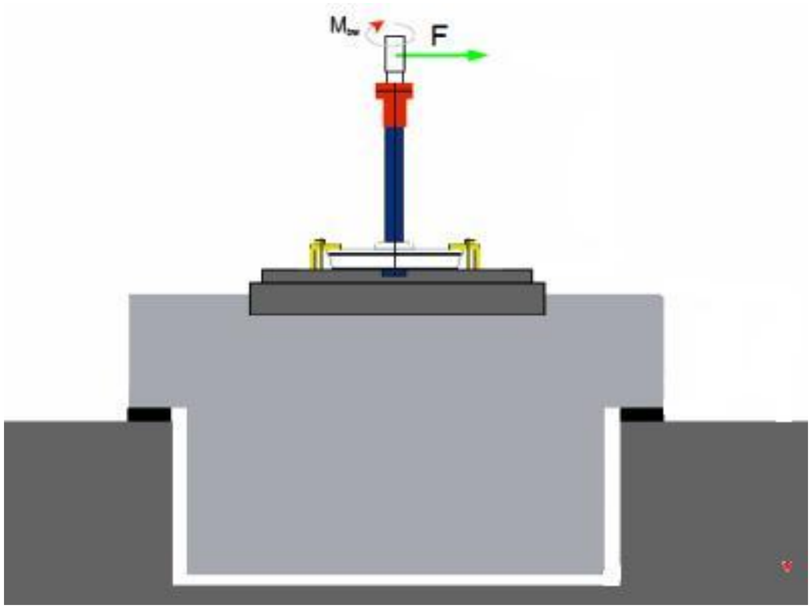
# Task 3.1 Definition of test methods

Two possible methods for testing axles are defined and considered to be equivalent




**Vitry type test rig**

- symmetric axle
- 3 point rotating bending
- test control through load F
- static strain/load calibration



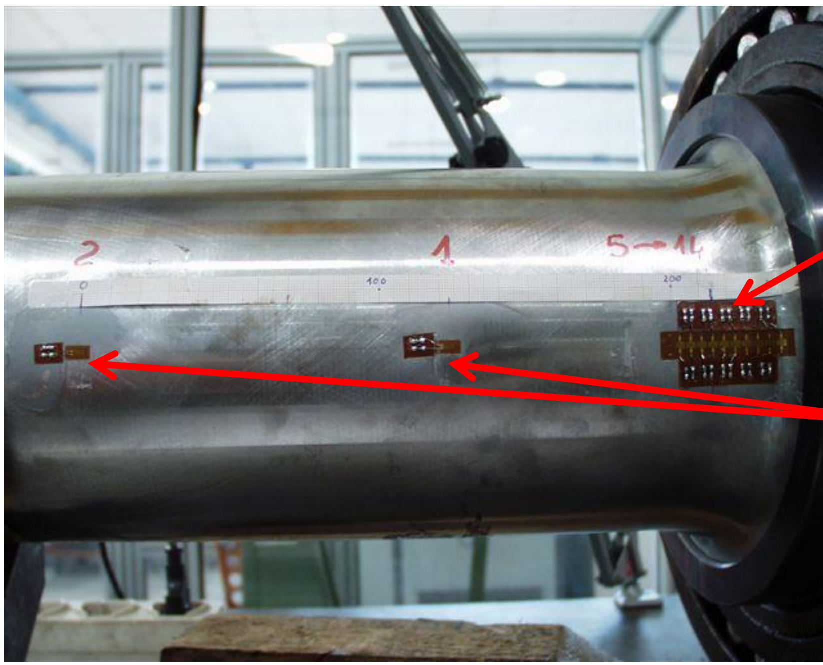

**Minden type test rig**

- standard axle design
- 2 point bending resonant excitation
- test control regulates motor speed to maintain desired strain

# Task 3.1 Definition of test methods

**F1 : free body fatigue limit**

It's the maximum local stress at the body-seat transition (measured by strain gauges) $s = E e$




- The maximum stress section is identified by an array of strain gauges and is the reference for the fatigue test

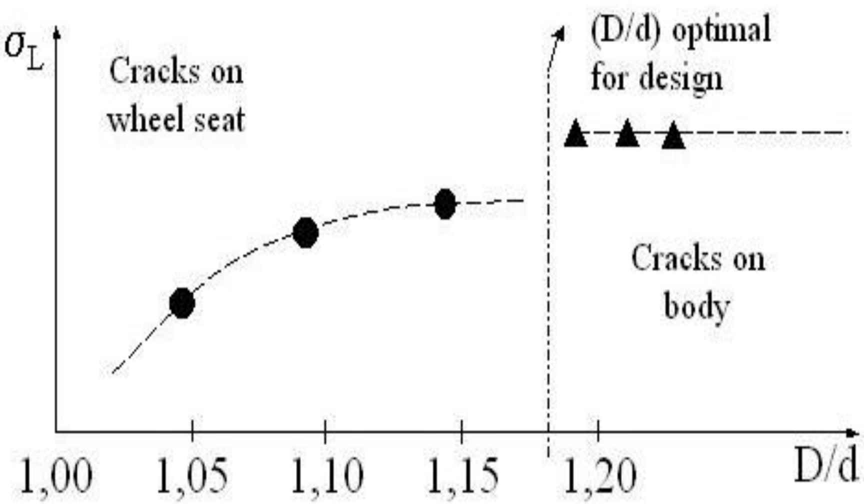
- The nominal stress is evaluated by interpolation of two extra strain gauges

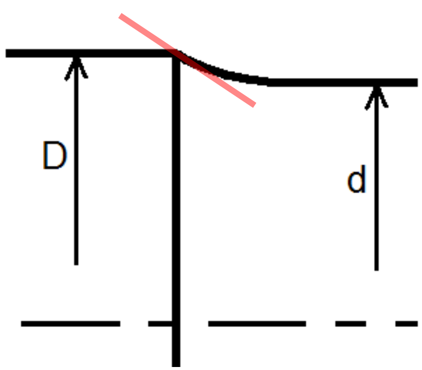
- The stress concentration factor : maximum local stress / nominal stress at starting of transition

# Task 3.1 Definition of test methods

**F3/F4 : press fitted seat fatigue limit  (solid or bore axle)**

It's the nominal stress at the seat edge




- The nominal stress is evaluated by interpolation of two strain gauges on the body

- Cracks appear as a consequence of the micro slip between seat and hub due to bending (Fretting phenomena)

- The fatigue limit depends on the diameter ratio (D/d), but also on the transition shape (particularly the transition slope near to the seat edge)

# Task 3.1 Definition of test methods

**Determination of the fatigue limit:**

- Stair case method is applied to determine load steps and sequences

- The statistical evaluation of the fatigue limit is done through the “Maximum Likelihood Method” (that can be applied when the load steps are not constant) providing the average fatigue limit and it standard deviation.

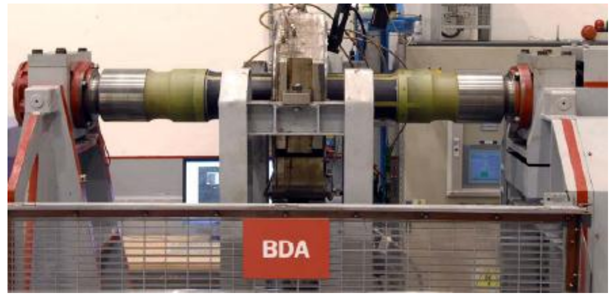
# Task 3.2 Material testing - Summary

- **F1 (full scale) under different conditions**
  - standard
  - typical power narrow axle grove between wheel and gear seats
  - higher machining roughness
  - blasted
  - corrosion
  - special metal coating

- **F4 (full scale) for different D/d**
  - D/d = 1,12
  - D/d = 1,08

**During this test campaign over 70 full scale axles 30 1/3 scale were tested**

# Task 3.2 Material testing - Test rigs involved in the testing

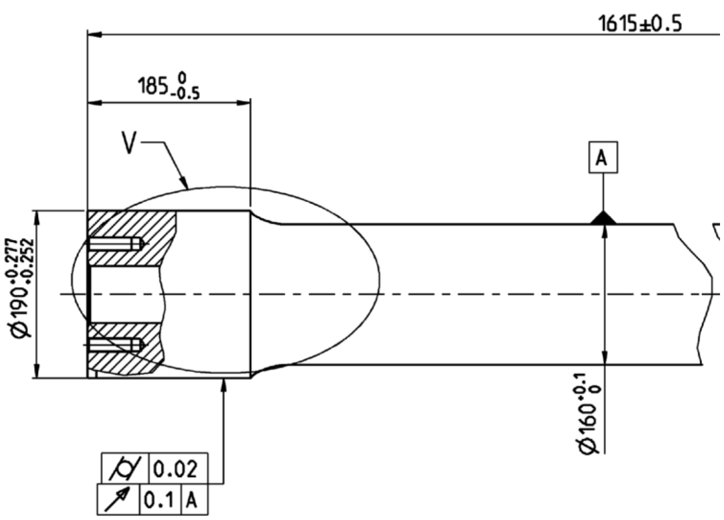


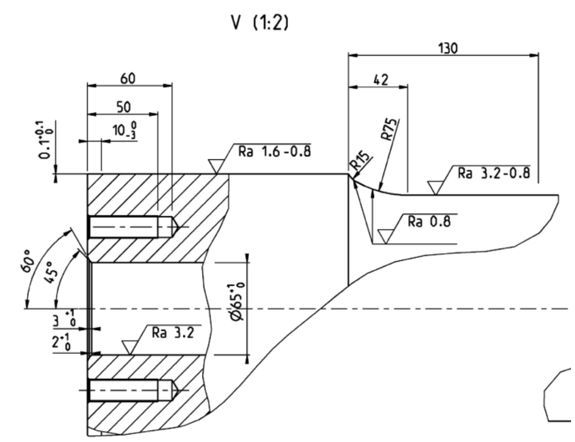

Vitry type test rig

Minden type test rig

# Task 3.2 Material testing

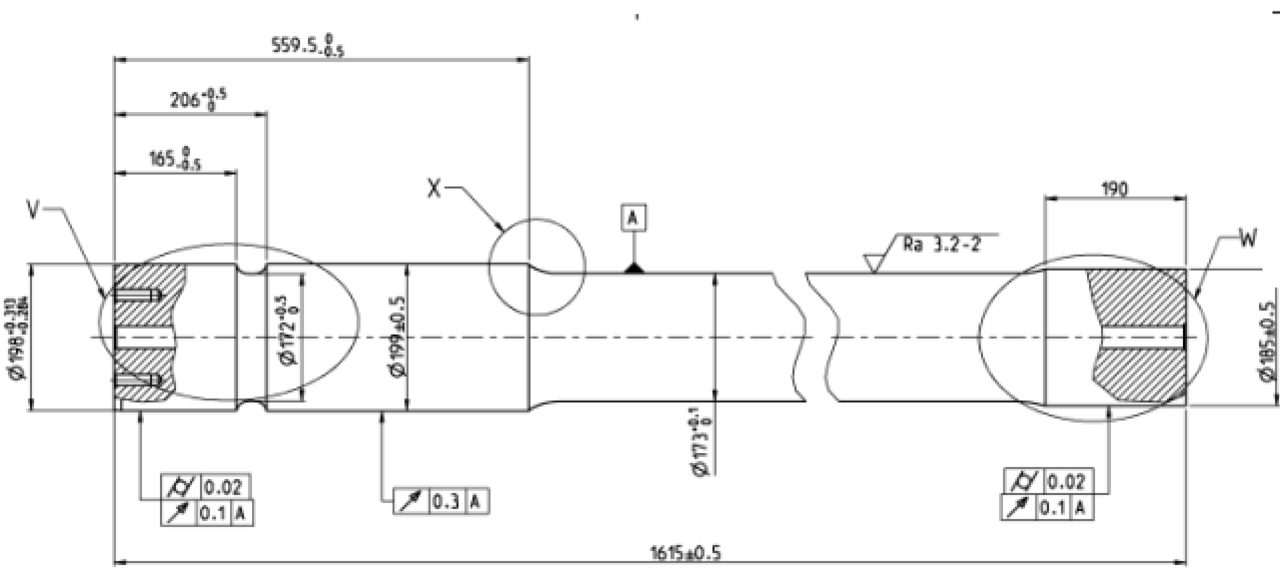
- **F1 (full scale) Standard surface – A4T**
  - d = 160 mm
  - D = 190 mm
  - D/d = 1,19
  - surface roughness = 0,8 and 3,2 Ra

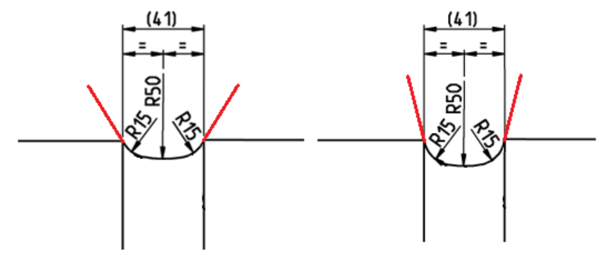


# Task 3.2 Material testing

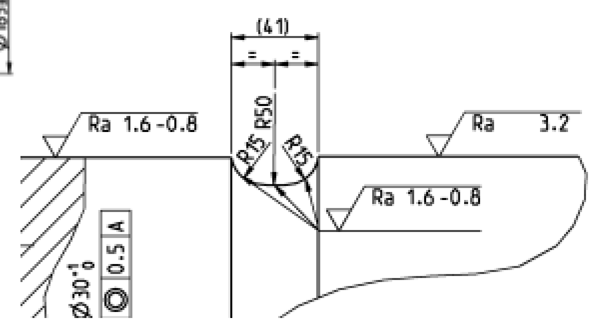
- **F1 (full scale) Powered axles – A4T**
  - Narrow grove between wheel and gear
  - The grove is designed deep in order to get a crack in the grove rather than in the seat




L = 41
D = 198
d = 180
D/d = 1,1

L = 41
D = 198
d = 172
D/d = 1,15

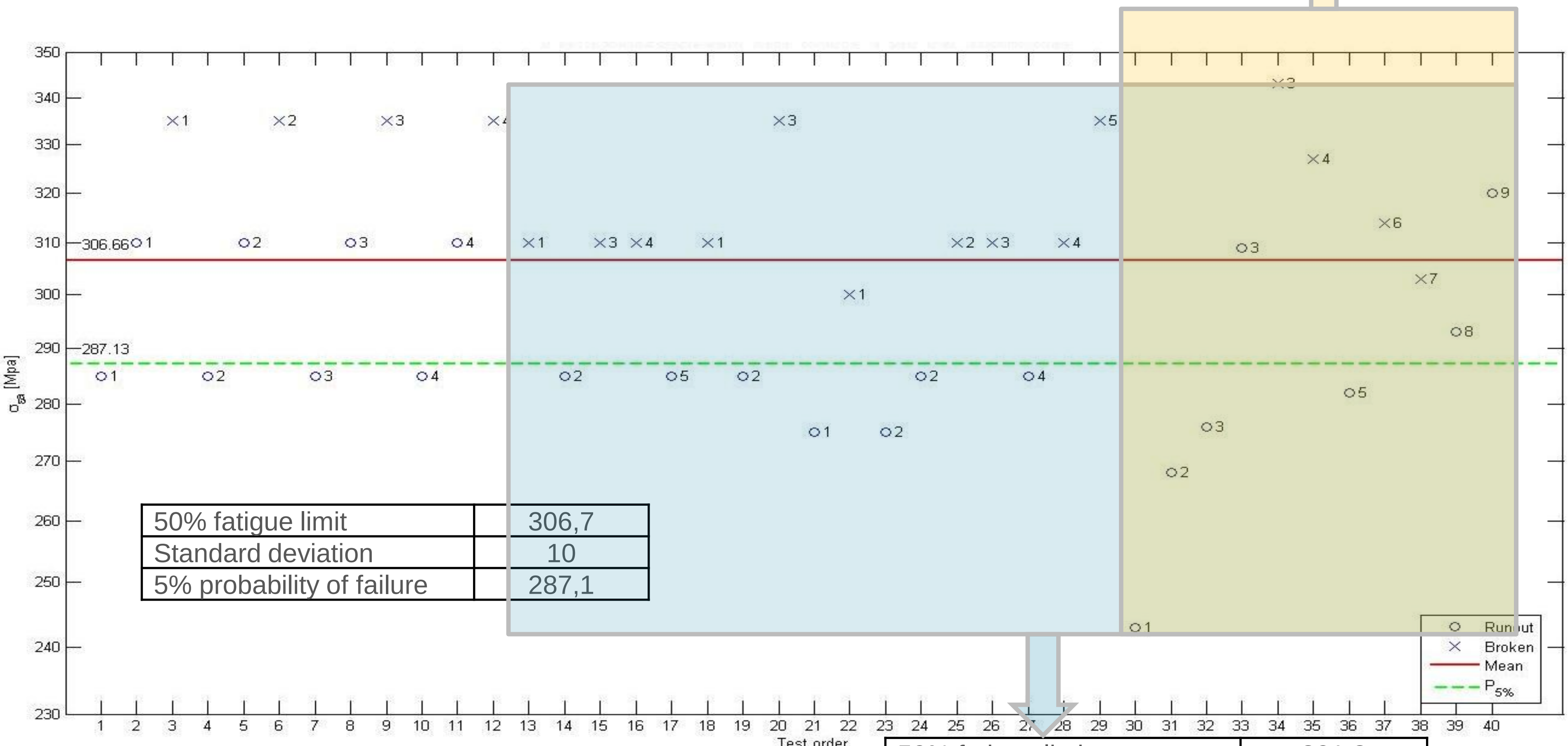


# Task 3.2 Material testing

- **F1 (full scale) Standard surface – A4T**

BMBF results :

| | |
|---|---|
| 50% fatigue limit | 311 |
| Standard deviation | 9,2 |
| 5% probability of failure | 285 |



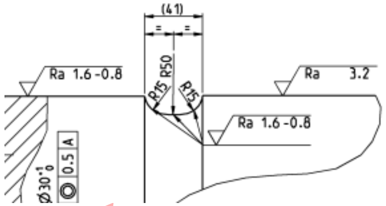

| | |
|---|---|
| 50% fatigue limit | 306,7 |
| Standard deviation | 10 |
| 5% probability of failure | 287,1 |

Excluding high strength material that gave cracks on the seats:

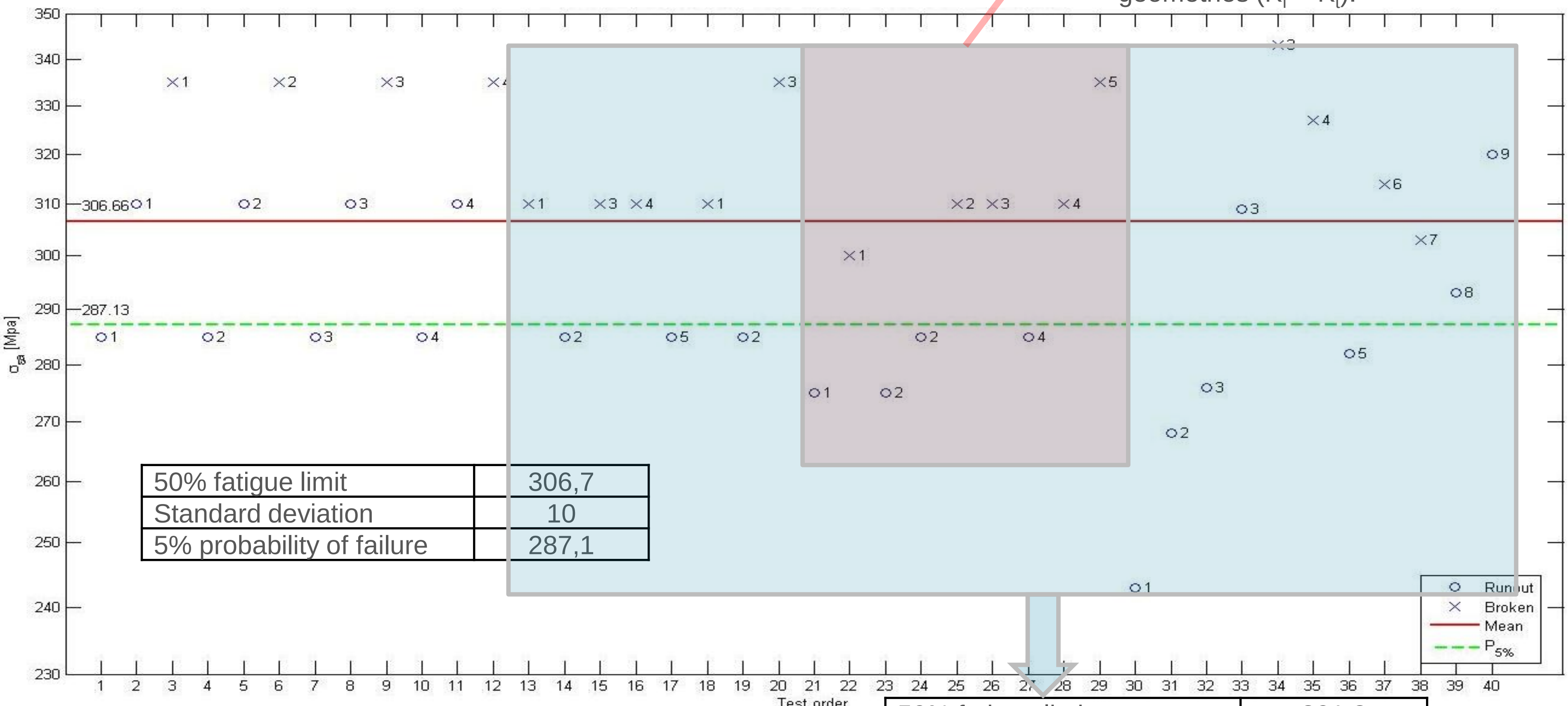
| | |
|---|---|
| 50% fatigue limit | 301,3 |
| Standard deviation | 9,2 |
| 5% probability of failure | 283,3 |

# Task 3.2 Material testing

- **F1 (full scale) Standard surface – A4T**




Results of grooved axles are coherent with the normal transitions: Local fatigue limit independent on geometries ($K_f = K_t$).

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Excluding high strength material that gave cracks on the seats:

| | |
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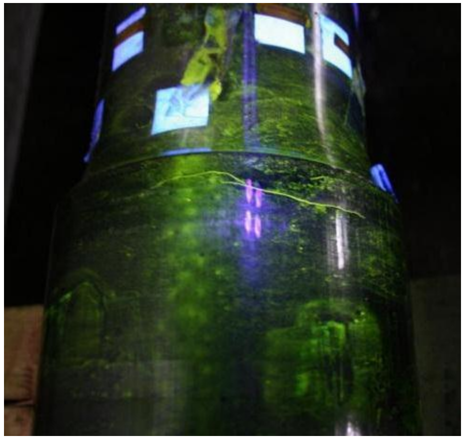
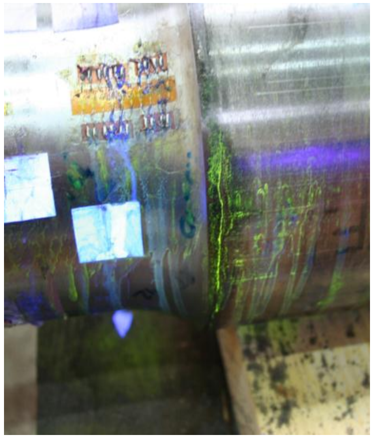
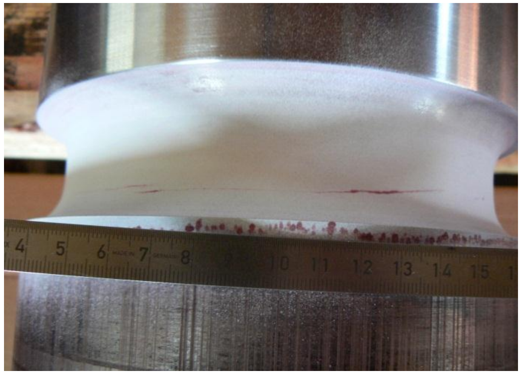
| 50% fatigue limit | 301,3 |
| Standard deviation | 9,2 |
| 5% probability of failure | 283,3 |

# Task 3.2 Material testing

- **F1 (full scale) Standard surface – A4T**
  - Examples of cracks obtained during the tests



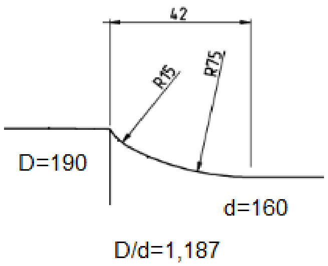


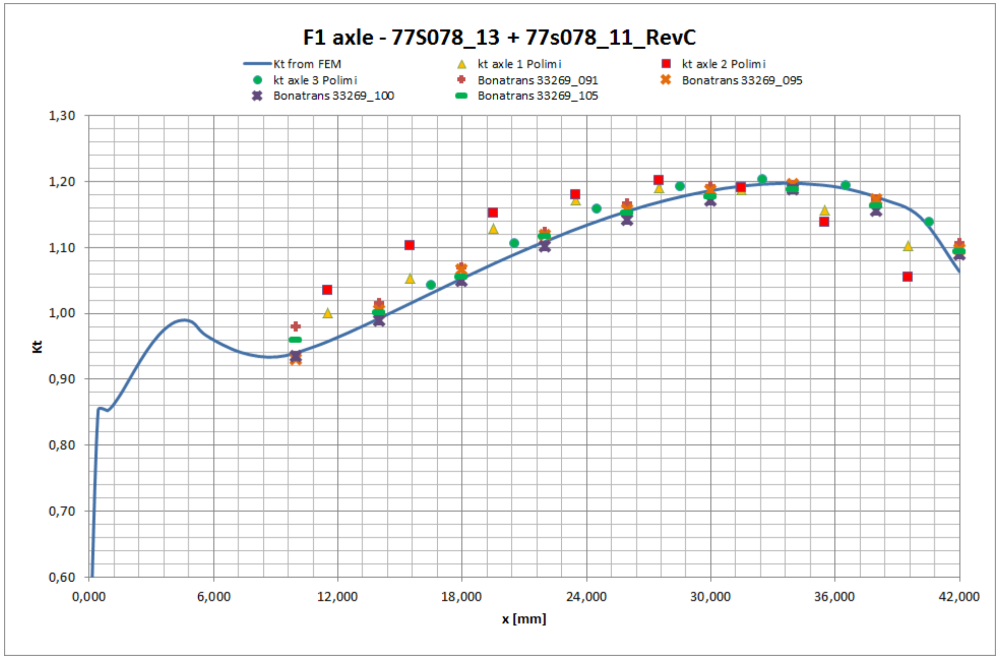




# Task 3.2 Material testing

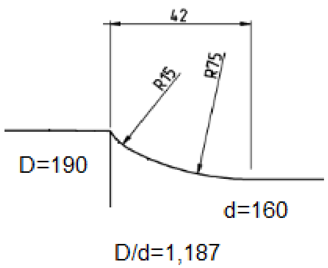
- **F1 (full scale) Standard surface – A4T**

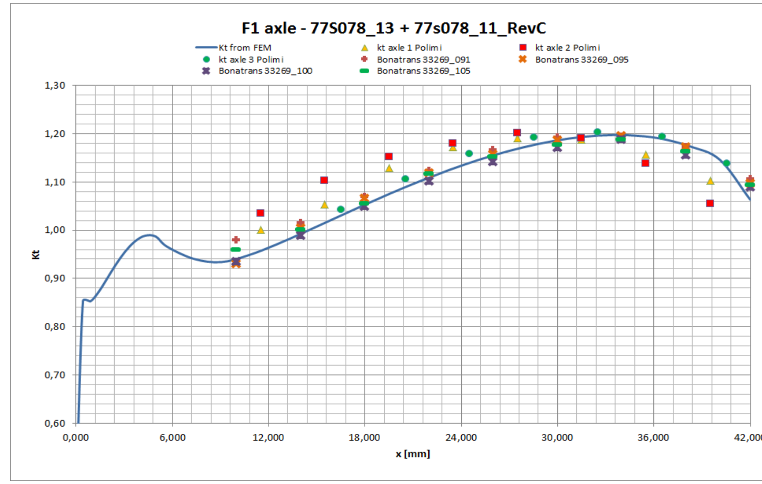


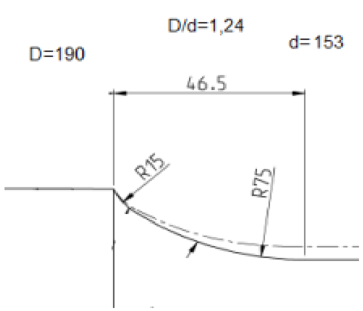



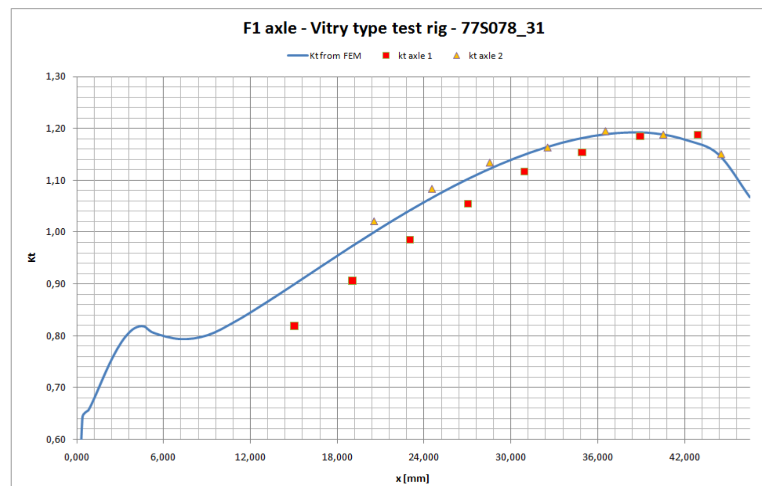
# Task 3.2 Material testing

- **F1 (full scale) Standard surface – A4T**
  - Stress concentration in the transitions



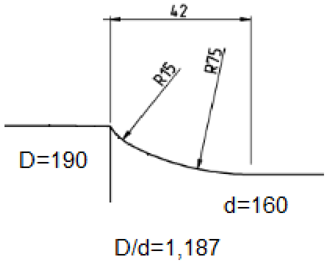



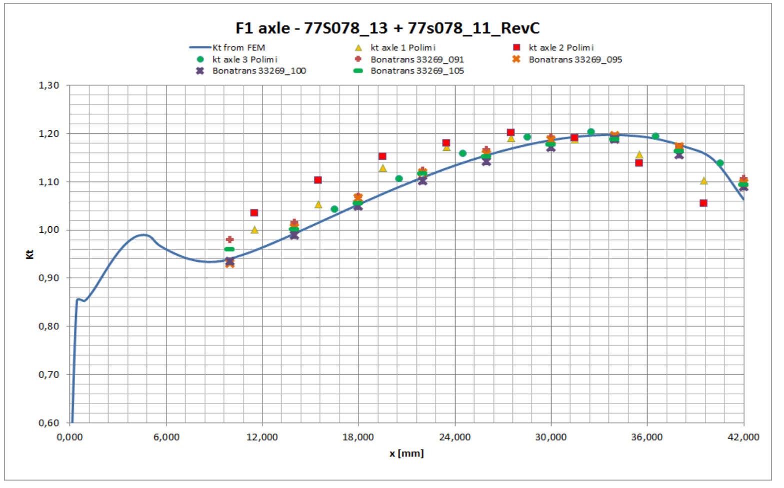



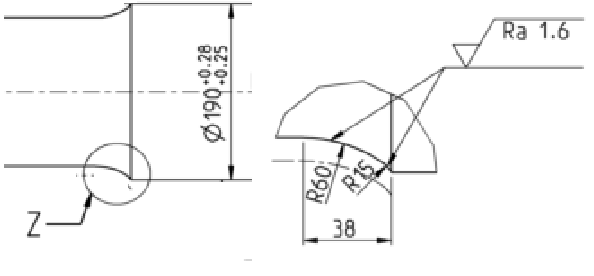



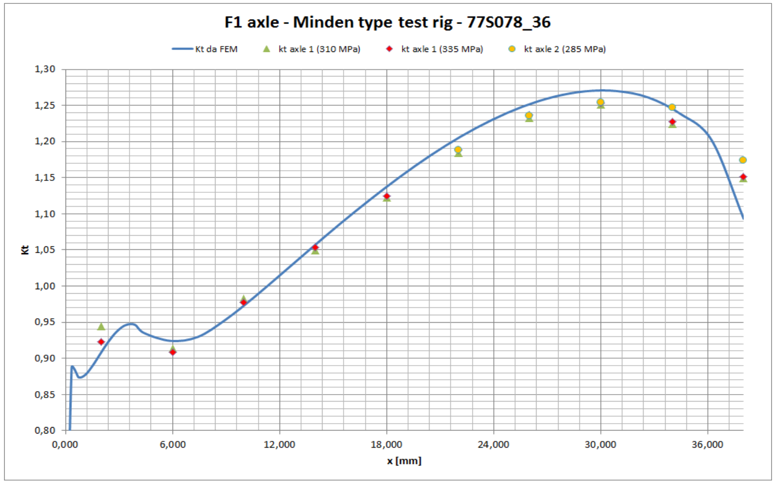
# Task 3.2 Material testing

- **F1 (full scale) Standard surface – A4T**
  - Stress concentration in the transitions



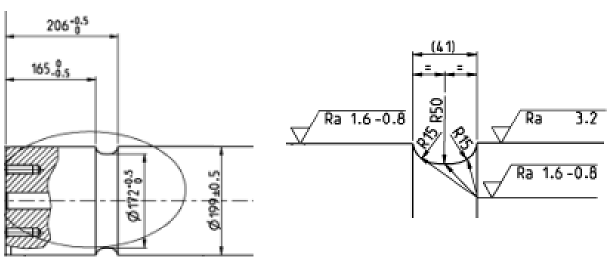



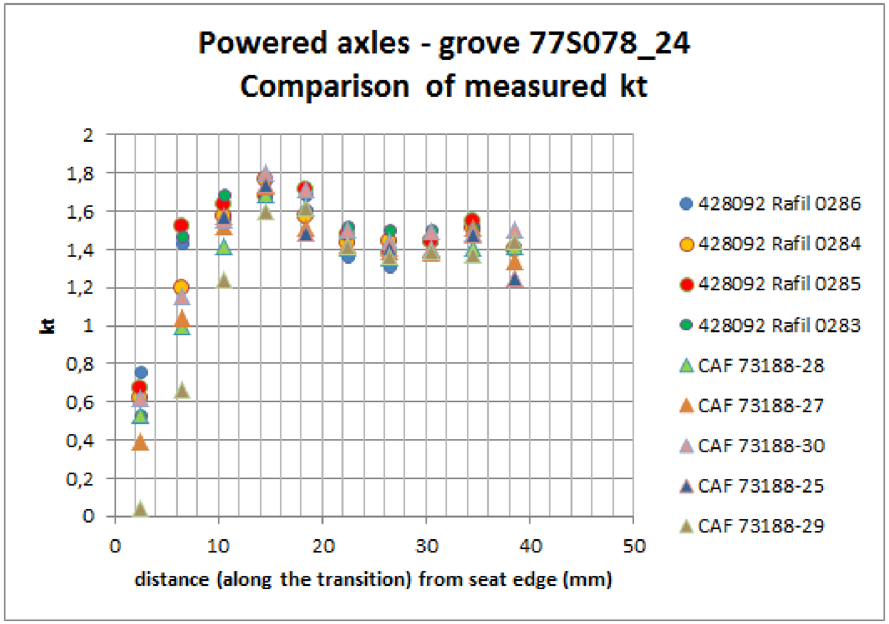



# Task 3.2 Material testing

- **F1 (full scale) Standard surface – A4T**
  - Stress concentration in the groves



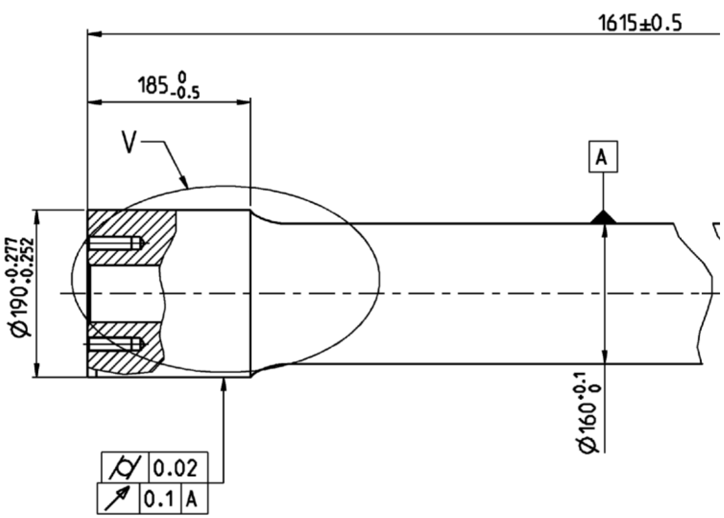


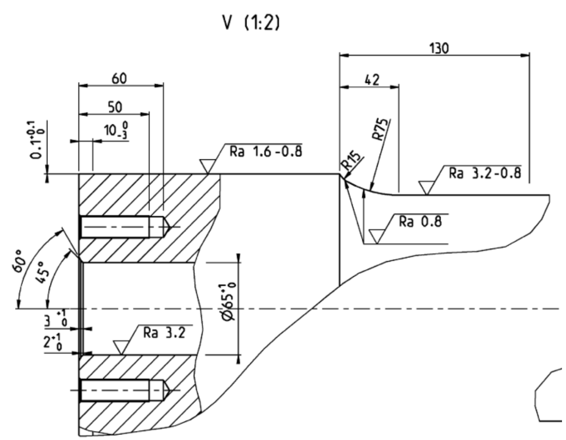
# Task 3.2 Material testing

- **F1 (1/3 scale and full scale) Modified surface to improve paint adhesion - A4T**

2 main different conditions are being tested :

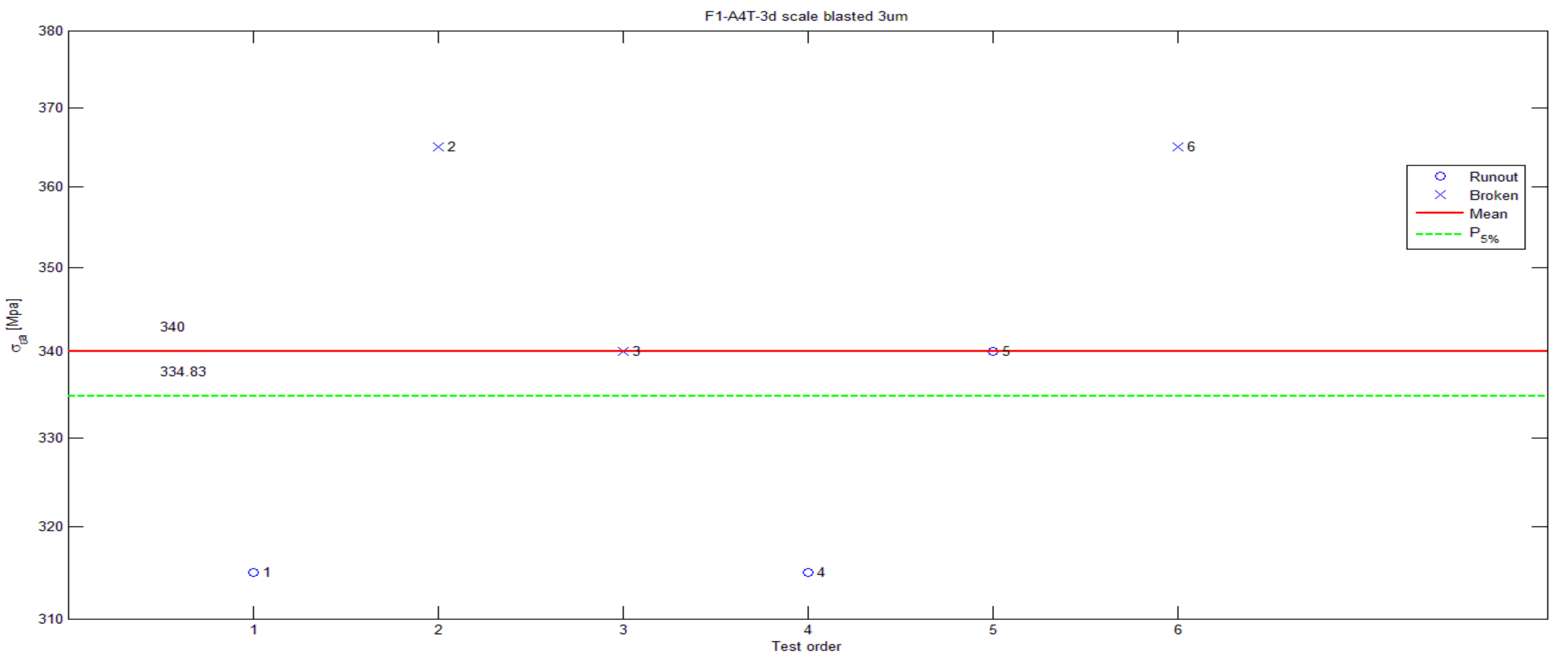
- machined with a roughness of 1,6 Ra then blasted with a roughness of 3,2 Ra
- machined with a roughness of 1,6 Ra then blasted with a roughness of 6,3 Ra



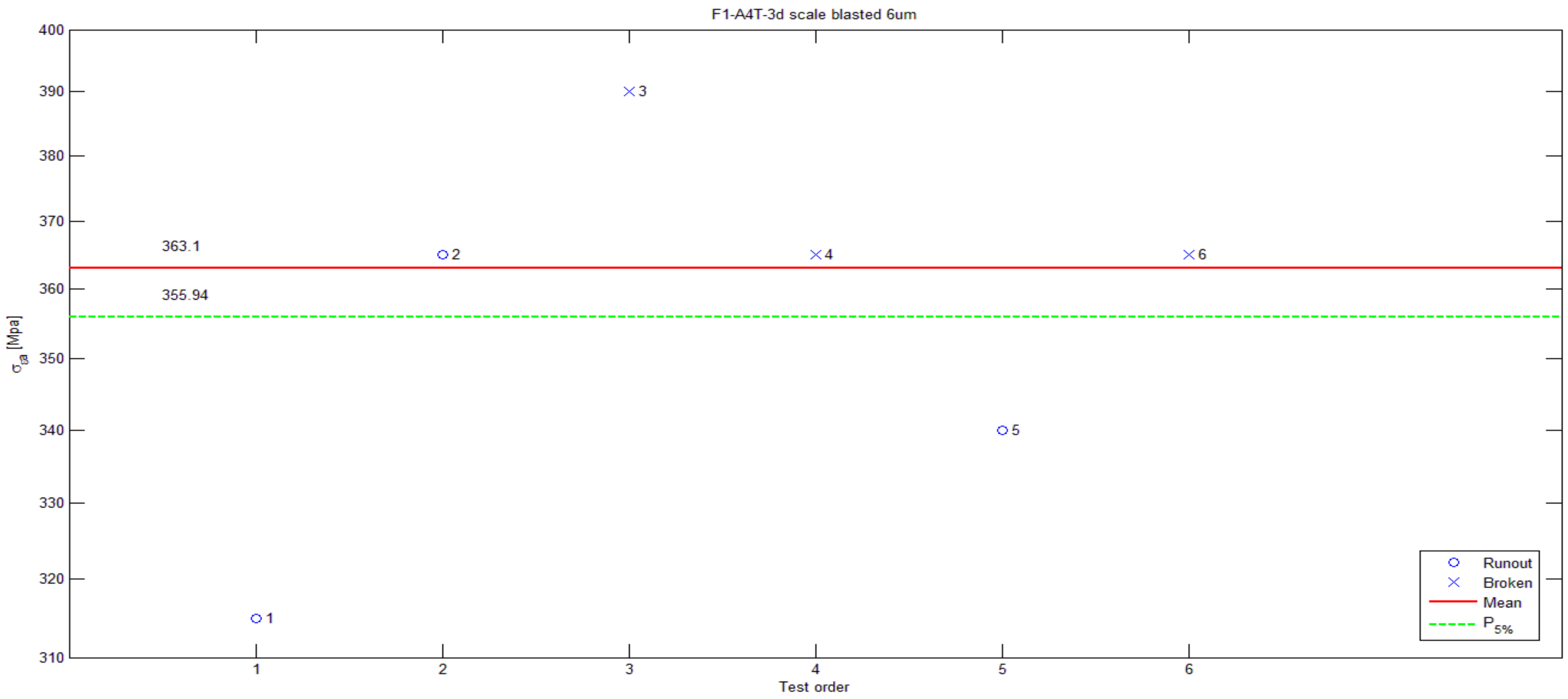
# Task 3.2 Material testing

- **F1 (1/3 scale A4T) Modified surface to improve paint adhesion**
  - Results of 1/3 scale blasted surface (3,2 Ra) EA4T axles; average fatigue limit = 340 MPa



# Task 3.2 Material testing

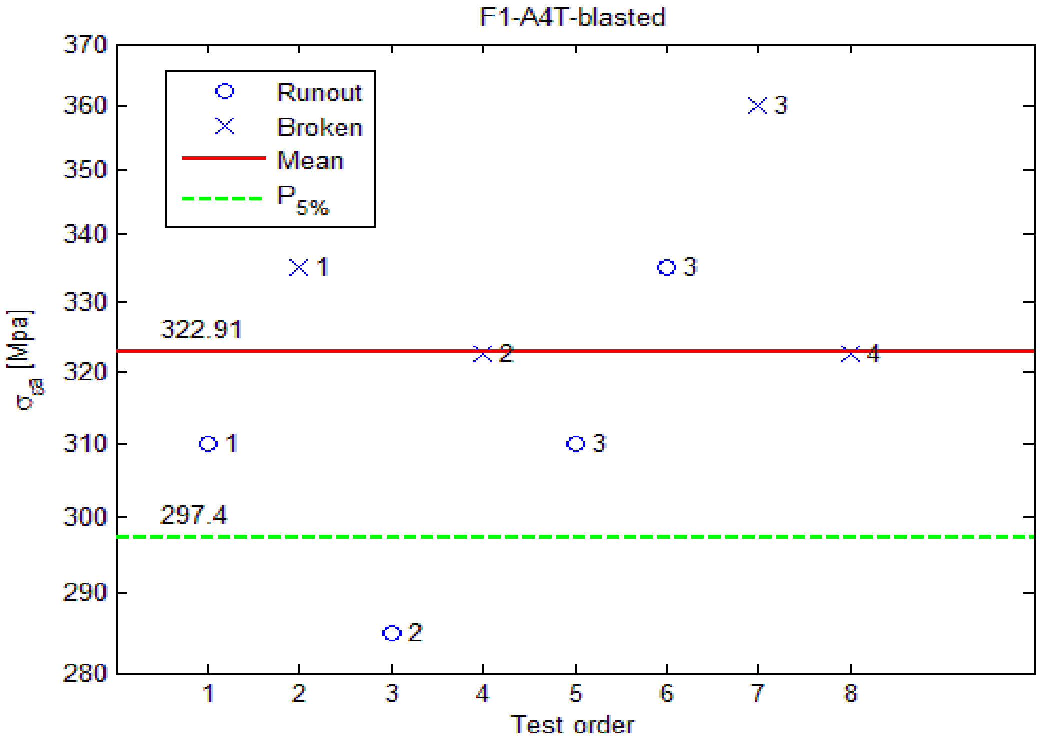
- **F1 (1/3 scale A4T) Modified surface to improve paint adhesion**
  - Results of 1/3 scale blasted surface (6,3 Ra) EA4T axles; average fatigue limit = 363 MPa

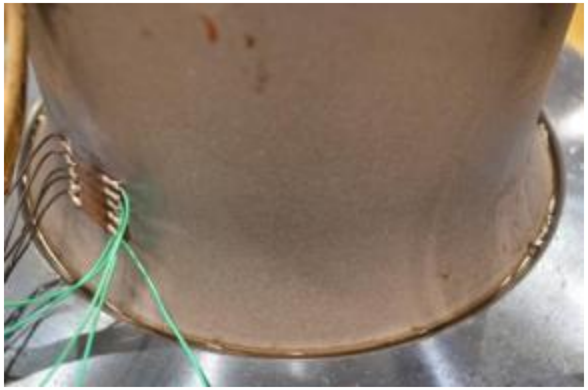


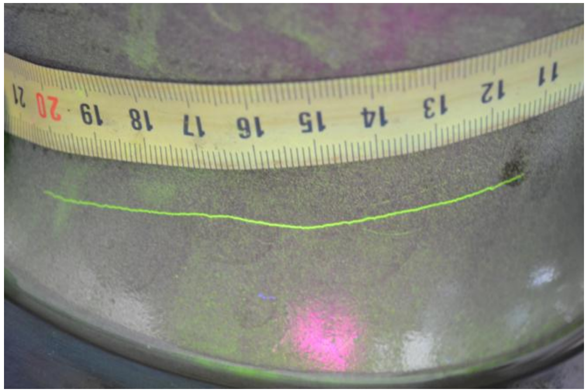
# Task 3.2 Material testing

- **F1 (full scale A4T) Modified surface to improve paint adhesion**

Stair case fatigue test results of F1 A4T axles blasted at a roughness of 6-7 Ra





| | |
|---|---|
| 50% fatigue limit | 322,9 |
| Standard deviation | 13 |
| 5% probability of failure | 297,4 |

# Task 3.2 Material testing

- **F1 (1/3 scale and full scale A4T) Modified surface to improve paint adhesion**

| | 50% fatigue limit | 5% probability of failure |
|---|---|---|
| | MPa | MPa |
| 1/3 scale blasted surface (3,2 Ra) | 340 | |
| 1/3 scale blasted surface (6,3 Ra) | 363 | |
| Full scale standard surface | 307 | 287 |
| Full scale axles blasted (6-7 Ra) | 323 | 297 |

Increase of the fatigue limit is probably due to the compressive stresses generated by the blasting process

SEVENTH FRAMEWORK PROGRAMME

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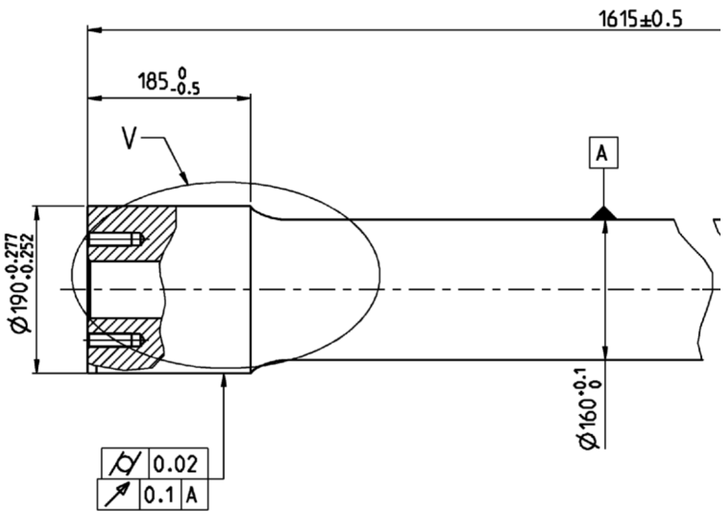
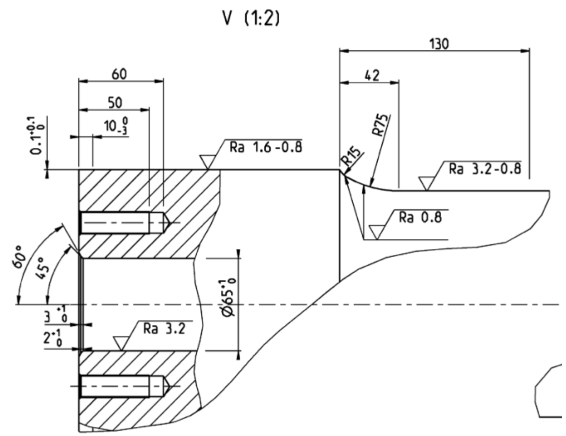
# Task 3.2 Material testing

- **F1 (full scale) Standard surface – A1N**
  - d = 160 mm
  - D = 190 mm
  - D/d = 1,19
  - surface roughness = 0,8 and 3,2 Ra



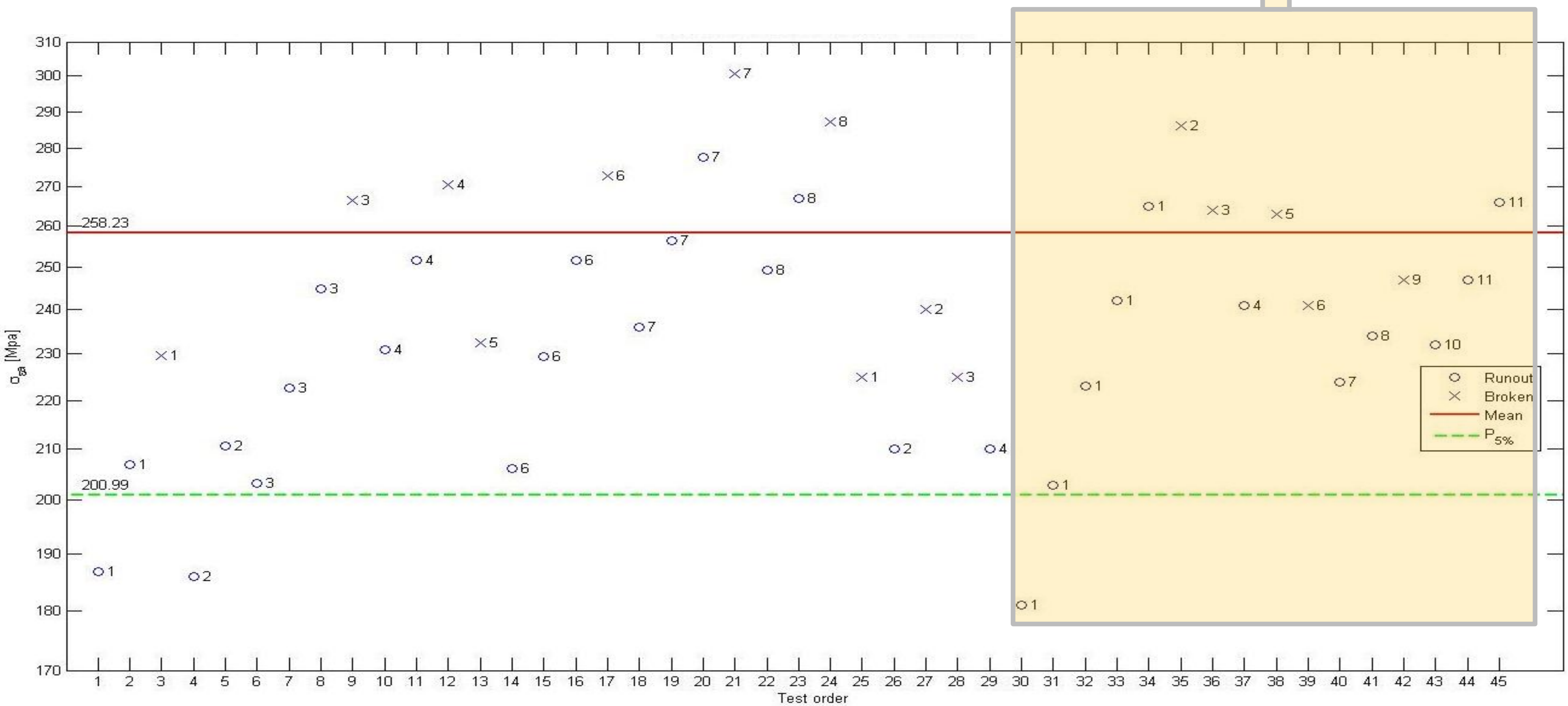



# Task 3.2 Material testing

- **F1 (full scale) Standard surface – A1N**

BMBF results :
the 50% fatigue limit doesn't change

| | |
|---|---|
| 50% fatigue limit | 257,9 |
| Standard deviation | 17,3 |
| 5% probability of failure | 223,9 |

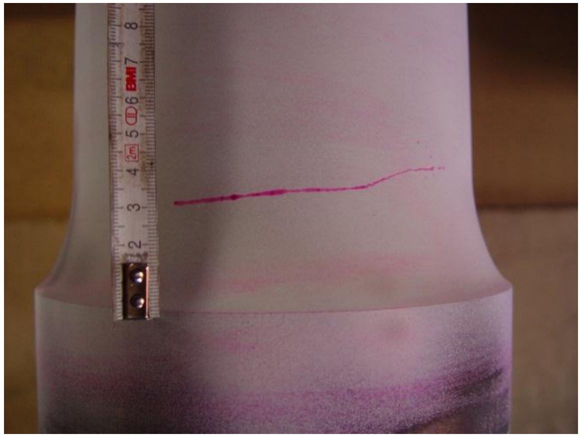


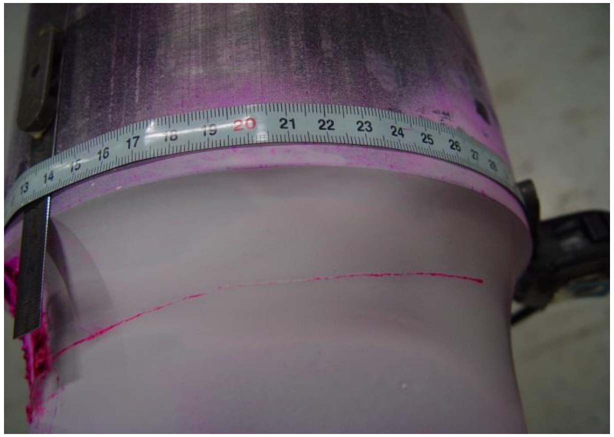

| | |
|---|---|
| 50% fatigue limit | 258,2 |
| Standard deviation | 29,2 |
| 5% probability of failure | 201 |

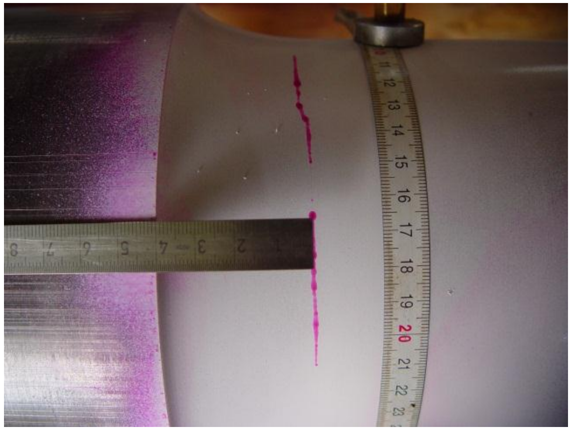
High value !

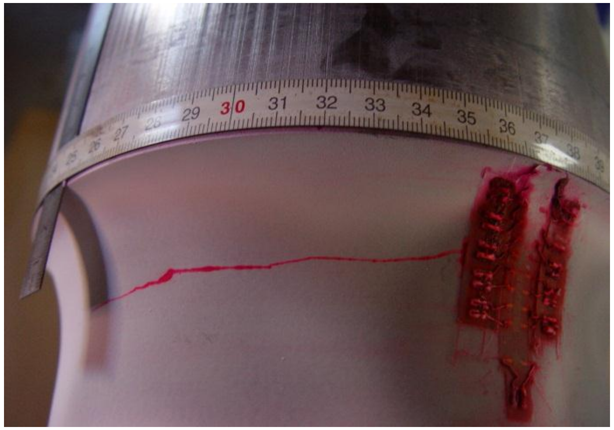
# Task 3.2 Material testing

- **F1 (full scale) Standard surface – A1N**
  - For A1N cracks appear all on the base of the transition (never on the seat)









# Task 3.2 Material testing

- **F1 (full scale) Effect of corrosion**

  Unpainted axles are normally used by SNCB (Belgium Railways);

  Axles show a uniform corrosion

  Axles are in A1N steel grade and have been in service for 10 year

D=188, d=160, D/d=1,175


SEVENTH FRAMEWORK PROGRAMME

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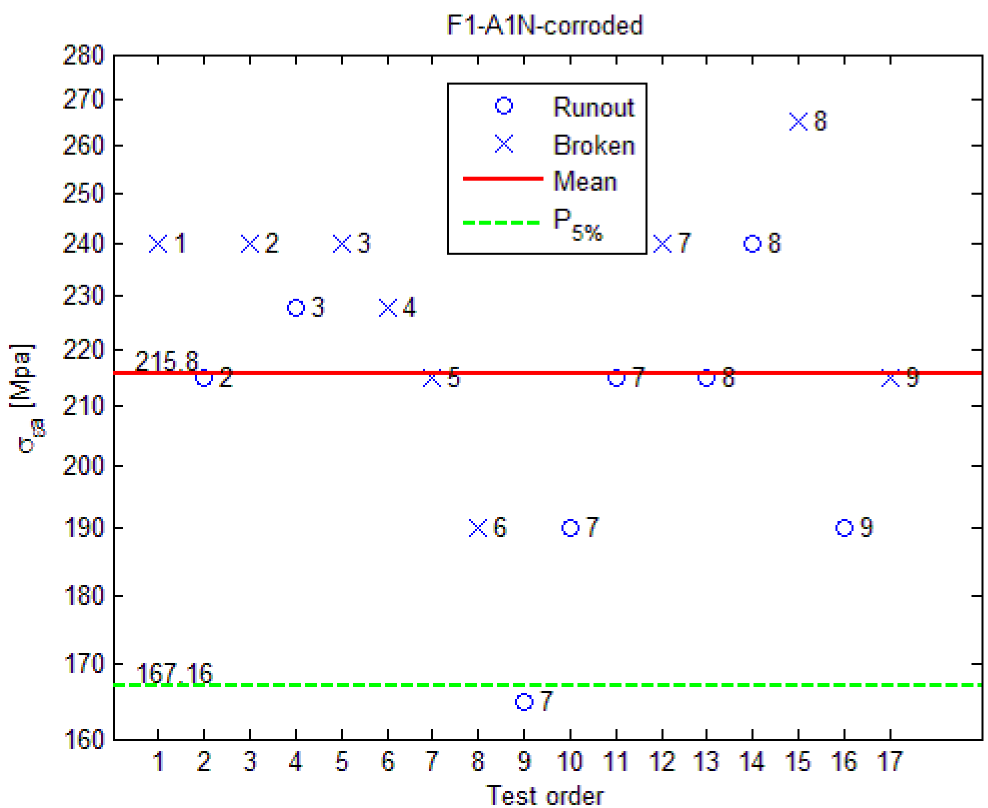
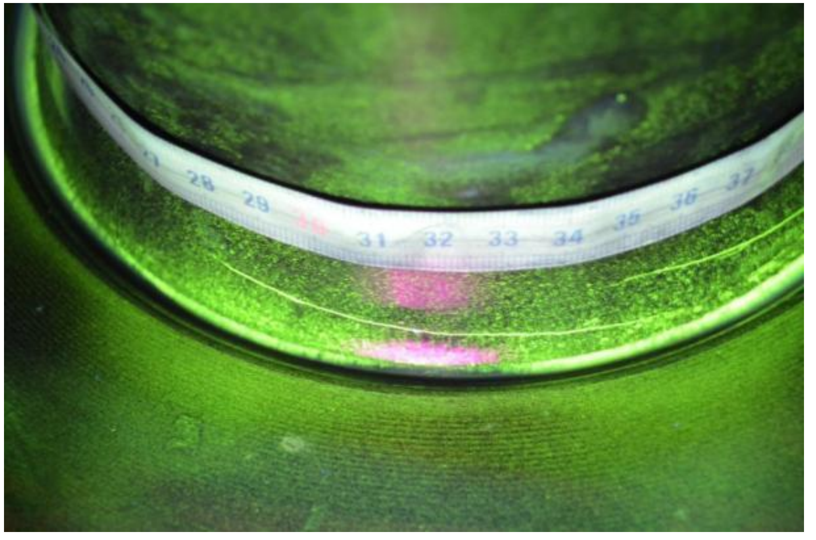
# Task 3.2 Material testing

- **F1 (full scale) Effect of corrosion**
  - Unpainted axles are normally used by SNCB (Belgium Railways);
  - Axles show a uniform corrosion
  - Axles are in A1N steel grade and have been in service for 10 year



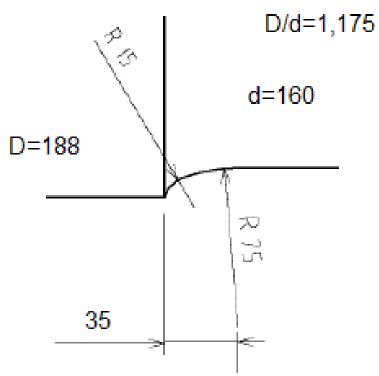



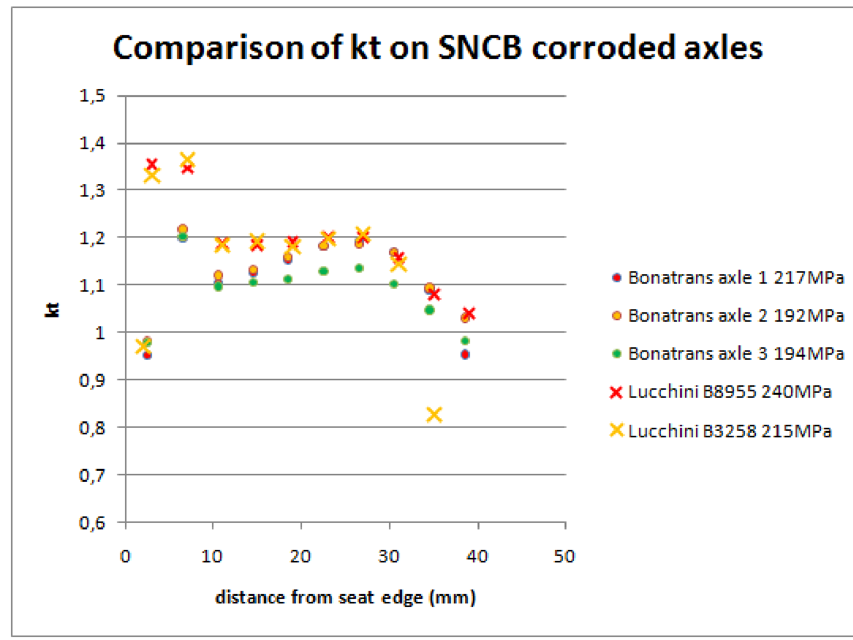
| | |
|---|---|
| 50% fatigue limit | 215,8 |
| Standard deviation | 24,8 |
| 5% probability of failure | 167,2 |

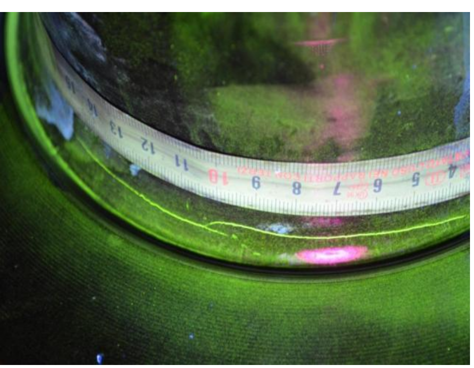
# Task 3.2 Material testing

- **F1 (full scale) Effect of corrosion**

  It’s important to notice that for these specific axles, the actual $k_t$ factor shows a higher maxima in the 15mm transition radius demonstrating how FEM analysis of stress concentration is useful to improve axle transition designs



# Task 3.2 Material testing

- **F1 (full scale) Effect of corrosion**
  Comparison of Standard surface and unpainted corroded from service

| | | Average Fatigue Limit | Standard deviation | Fatigue Limit 5% | EN13260 EN13261 |
|---|---|---|---|---|---|
| EA1N | Standard | 258 | 29 | 201 | 200 |
| | Corroded | 216 | 24,8 | 167 | 154 |

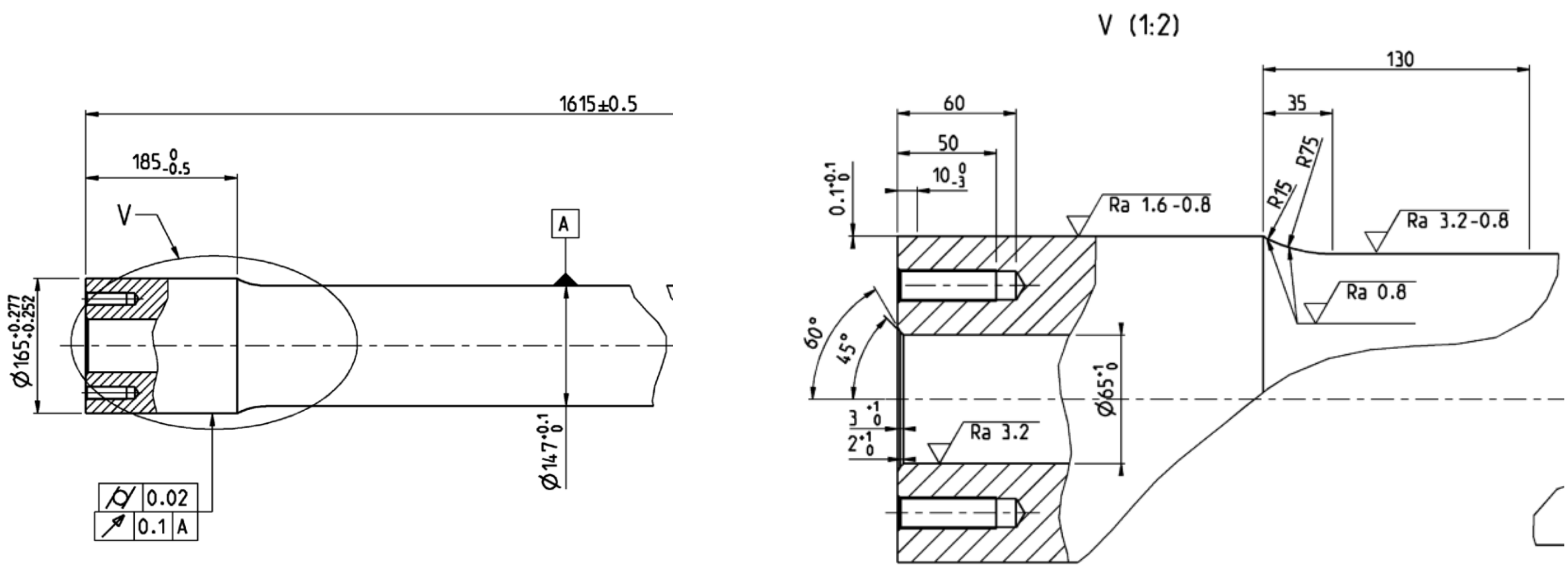
- The results of the fatigue tests performed on unpainted corroded axles from service show a reduction of about 17% from the standard new axles.
- In this case the additional safety factor to be used in the design would be : 258/216 = 1,19 instead of 1,3 as reported in the European Standards, but it must be considered that this is a specific condition and may not be valid in general.
- For local corrosion the damaging effect will be more critical than for uniform distributed corrosion.
- The coating of painted axles shall always be repaired whenever coating detachments are found during maintenance visual inspections (in line with EVIC guidelines).

# Task 3.2 Material testing

- **F4 (full scale) D/d = 1,12**

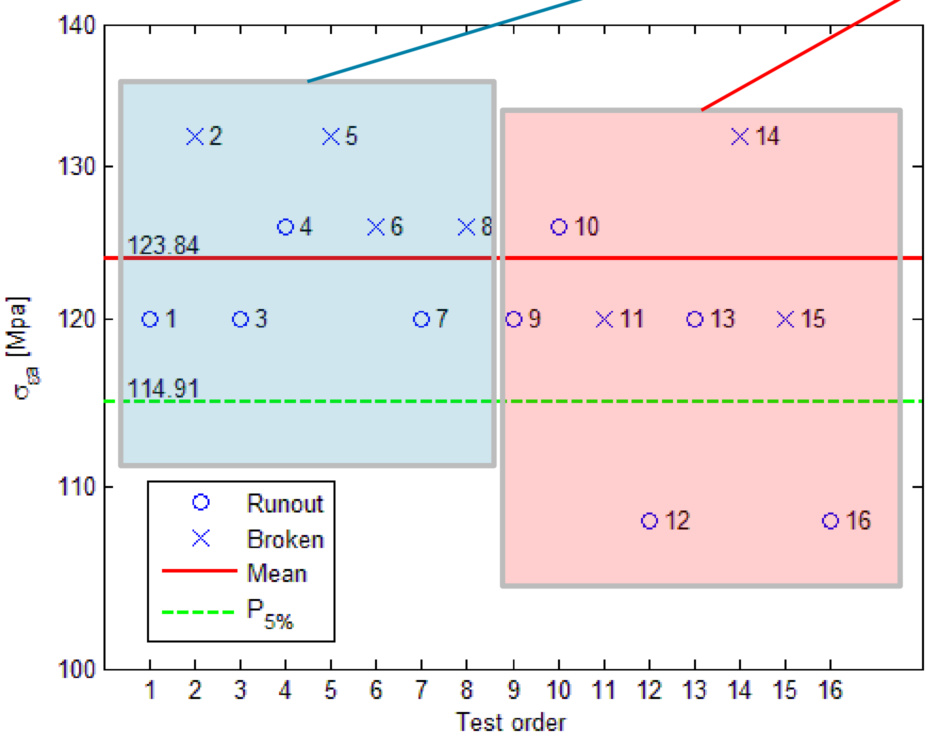
1,12 is the ratio required for the F4 qualification of axles; for A4T, F4 = 132 MPa

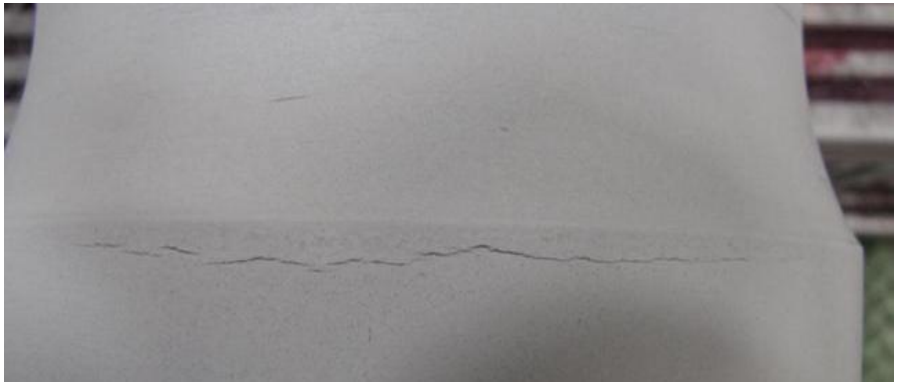
The transition geometry is representative of a standard axle with a reprofiled seat.



# Task 3.2 Material testing

- **F4 (full scale) D/d = 1,12**
  - 1,12 is the ratio required for the F4 qualification of axles; for A4T, F4 = 132 MPa
  - The transition geometry is representative of a standard axle with a reprofiled seat.
  - Test performed both on the Minden and Vitry type test rig



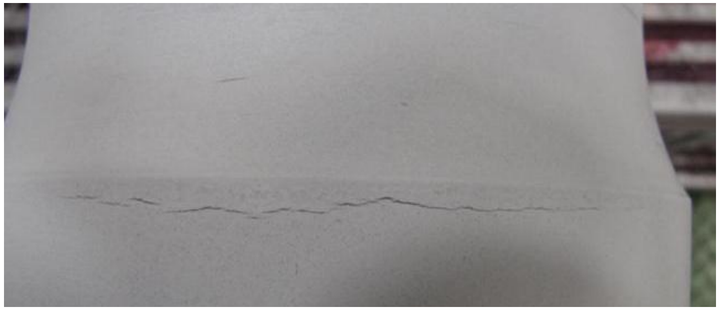



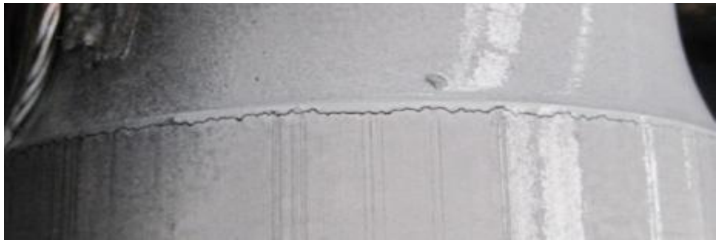
| | |
|---|---|
| 50% fatigue limit | 123,8 |
| Standard deviation | 4,5 |
| 5% probability of failure | 114,9 |

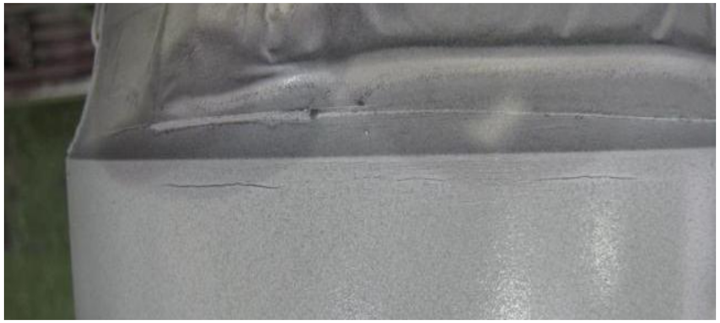
# Task 3.2 Material testing

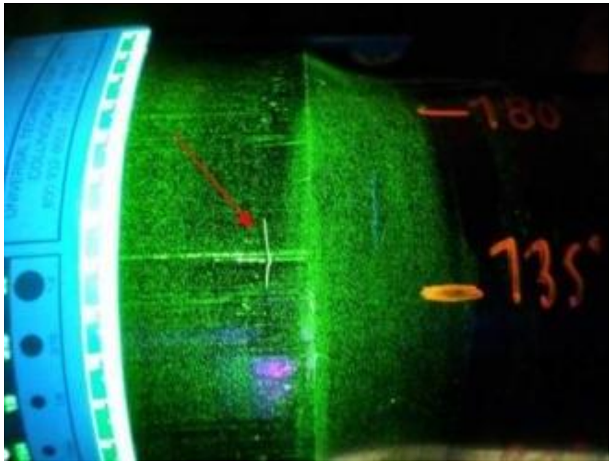
- **F4 (full scale) D/d = 1,12**

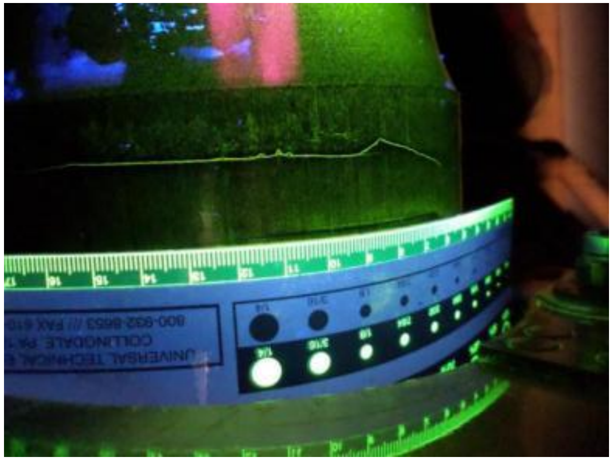
Example of crack detected during the tests









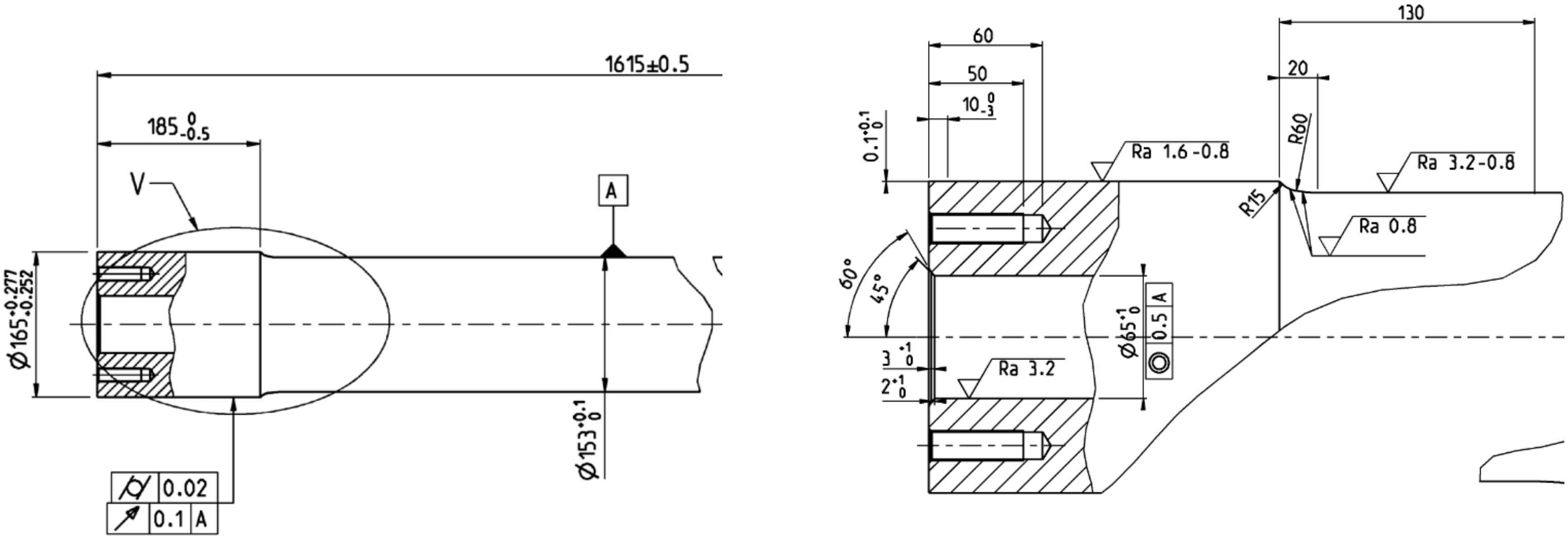


# Task 3.2 Material testing

- **F4 (full scale) D/d = 1,08**

1,08 ratio may be used on powered axles

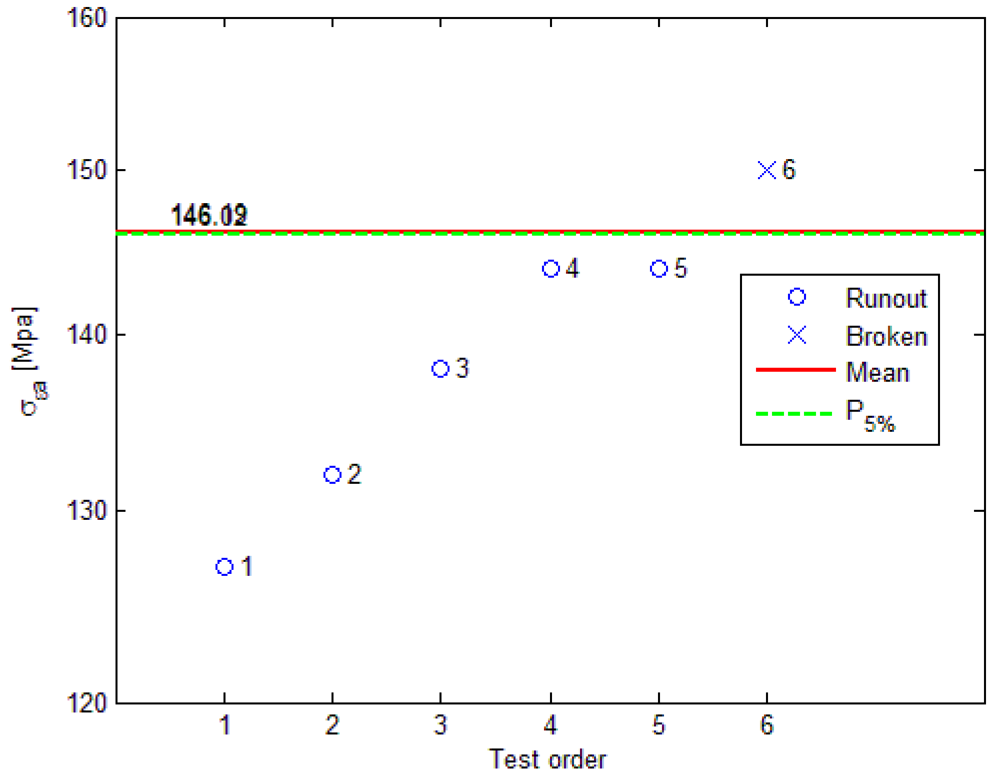
The chosen transition is shorter (20 mm)



# Task 3.2 Material testing

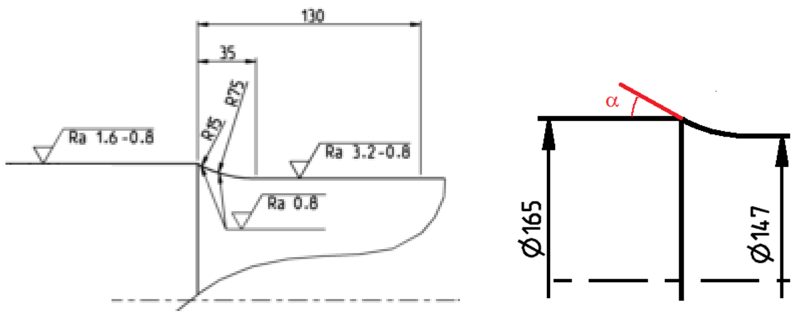
- **F4 (full scale) D/d = 1,08**

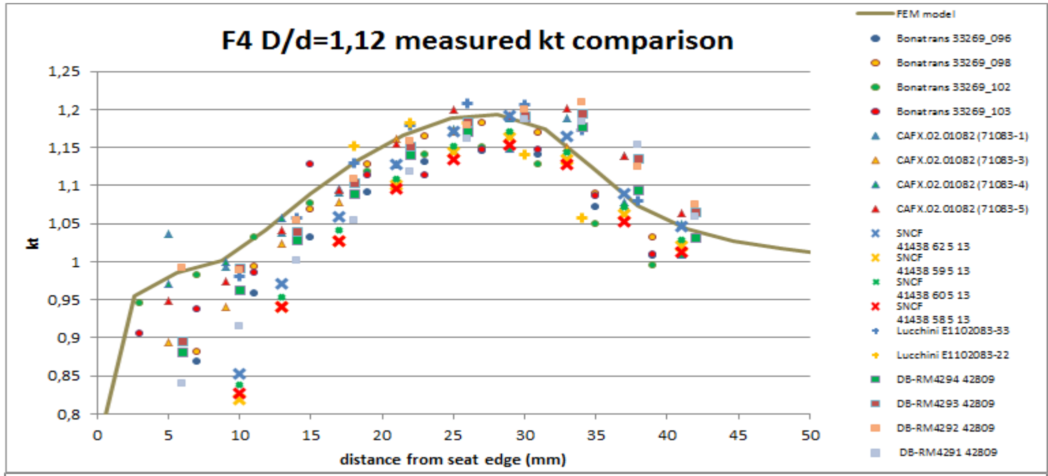
1,08 ratio may be used on powered axles
The chosen transition is shorter (20 mm)

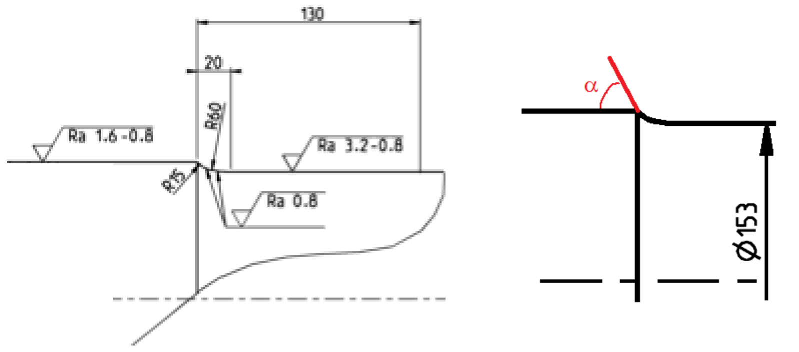


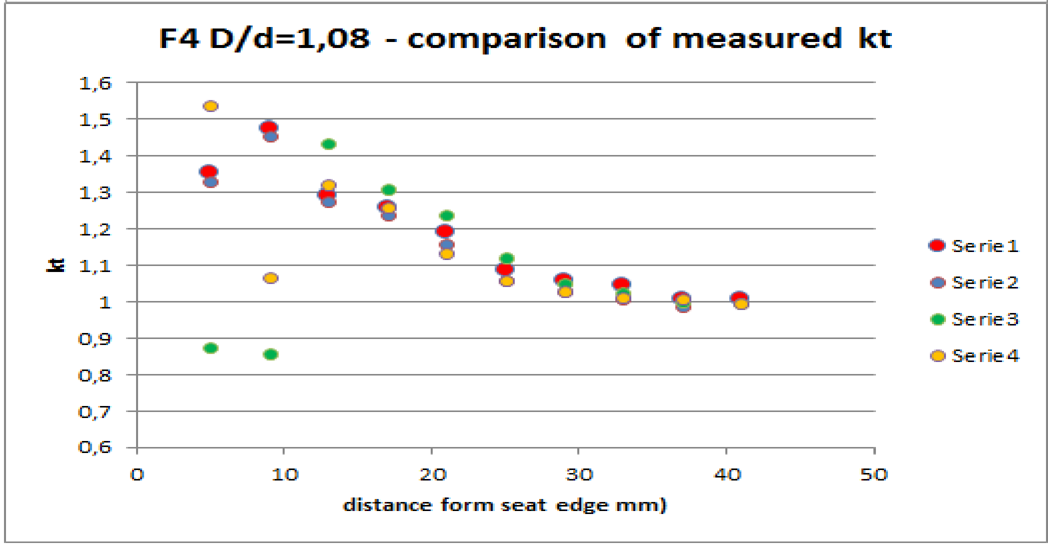

| | |
|---|---|
| 50% fatigue limit | 146 |
| Standard deviation | / |
| 5% probability of failure | / |

- **F4 (full scale) comparison between D/d = 1,12 and 1,08**
  - Stress concentration factors along the transitions



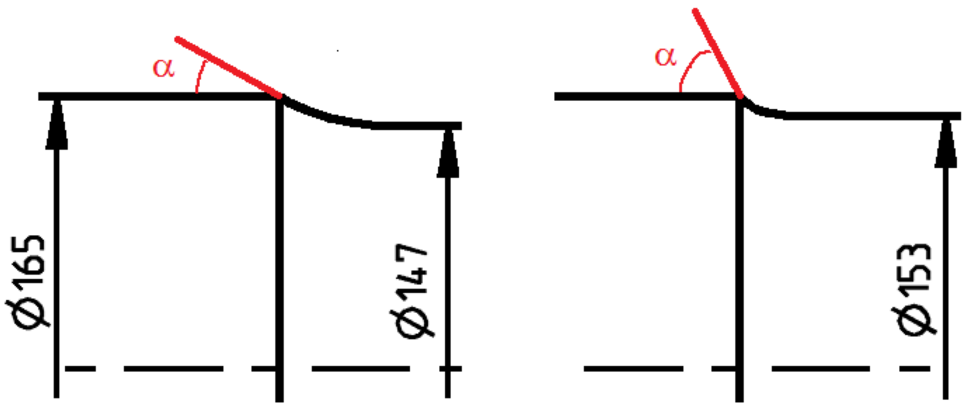



• **F4 (full scale) comparison between D/d = 1,12 and 1,08**

| Nominal stress at seat edge (MPa) | 50% | 5% | 50%/5% | EN |
|---|---|---|---|---|
| F4 A4T D/d=1,12 | 124 | 115 | 1,08 | 132 |
| F4 A4T D/d=1,08 | 146 | .. | | .. |




## Conclusions:

• wheel-seat fretting resistance can be increased by optimizing the fillet geometry (increase a or D/d)

• the draw back is that stress concentration in the transition increases but it can be easily controlled by FEM analysis (see WP2)

# Conclusions

Summary of fatigue limit results compared to reference values in the EN Standards

| | | | Average Fatigue Limit | Standard deviation | Fatigue Limit 5% | EN13260 EN13261 |
|---|---|---|---|---|---|---|
| F1 | EA4T | Standard | 307 | 10 | 287 | 240 |
| | | Blasted 6,3 Ra | 323 | 13 | 297 | / |
| | EA1N | Standard | 258 | 29 | 201 | 200 |
| | | Corroded | 215 | 24,8 | 167 | 154 |
| F4 | EA4T | D/d = 0,12 | 124 | 4,5 | 115 | 132 |
| | | D/d = 0,08 | 146 | / | / | / |

-17%

Effect of geometry transition

**Effect of fretting fatigue generated in the test**

# Conclusions (Proposals for Standard revision)

## *AXLE TRANSITIONS*

- *As shown $K_t$ factors determined through FEM model are generally 20% higher than in the EN.*
- *Axle can still be calculated by the beam theory (EN 13103), but then apply the real $K_t$ factors (FEM model).*
- *In this case local stress fatigue limits (higher than the ones in the EN) should be used (with a failure probability of 5%).*
- *Further investigation should address the values of the safety factors to be used; in the EN they depend on material, type of axle, including effects from unknown conditions of service loads and material strength scatter; methods developed in Euraxles-WP2 will allow to define appropriate values.*
- *In general the use of FEM models to verify the stress distribution in the transitions and groves will surely improve the axle design.*
- *It is shown that appropriate surface blasting of the surface can ensure no reduction of the fatigue limit.*
- *It is shown that unpainted corroded axles have a 17% lower fatigue limit compared to new axles.*

# Conclusions (Proposal for Standard revision)

*AXLE PRESS-FITTED SEATS*

● *It is proven that by applying the condition of acceptability that no crack indication should be found at the end of the fatigue tests, can lead to a reduction of the F4 fatigue limits.*

● *Nevertheless permissible stress should not be changed due to the positive feedback from the service.*

***The reason for the above is in the specific nature of the fretting fatigue phenomena: different from classical surface fatigue, fretting fatigue damage increases in a non linear way in relation to the friction coefficient that from a certain level of load enables dynamic slip damaging the axles seat surface.***

● *It is also shown that increasing the slope of the transition near the seat edge (and controlling the higher stress in this area) improves the fretting fatigue resistance of the press fitted seats.*

# Thank you for your attention