Material properties estimated by Small Punch "tensile" and creep tests;

CASE: 316L SLM material

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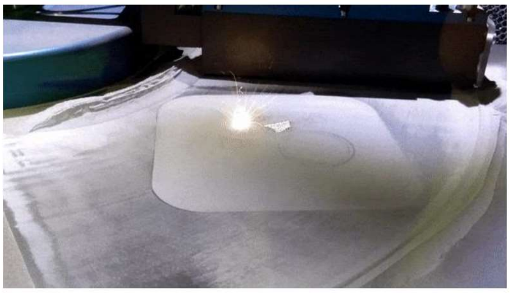
Background

The work presented here is the outcome of in-kind contribution to the ECCC working group 3B of ENGIE Laborelec and JRC.

Engie Laborelec has been involved in Additive Manufacturing (AM) of metals since 2015 and uses three different Selective Laser Melting (SLM) machines. The SLM500 machine has been fully optimized for printing 316L SLM material with mechanical properties fitting the corresponding ASTM standards for AM. However, creep testing was not yet carried out on this material.

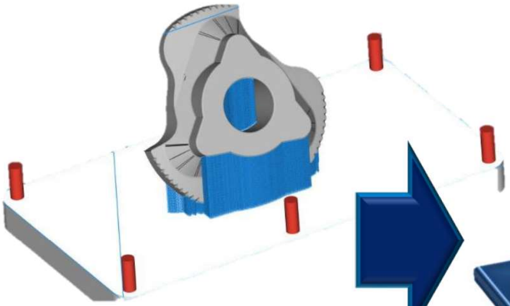


JRC was one of the active members on developing and promoting the standardization of the small punch test techniques for estimating tensile and creep properties. The new standard is supposed to be balloted on by the summer 2019.

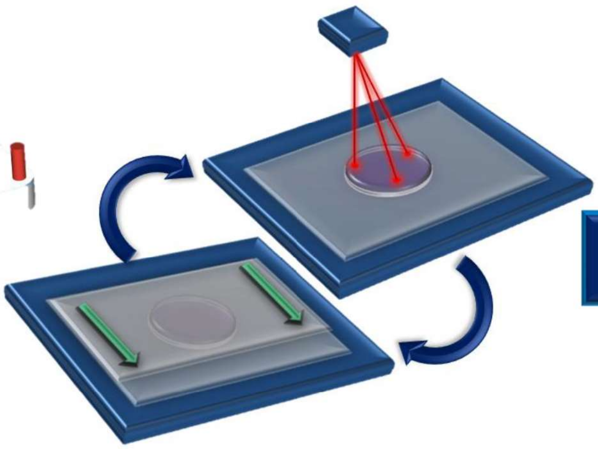
As a consequence JRC offered to test the SLM materials in accordance with the standard test set-up, testing methodologies and material property estimation recommendations.

Principle of AM

- Joining materials to make objects from **3D digital data**, usually **layer upon layer**, as opposed to subtractive manufacturing methodologies
- For metals, powder bed fusion technology (e.g. SLM) is one of the leading technologies



3D Geometry of the Part
Build Preparation



Layer by layer construction until the part is complete
Local fusion of successive metal powder layers using a high energy laser

Build Process is complete
(Post-Process required)

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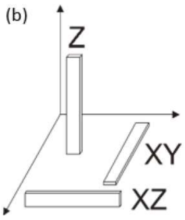
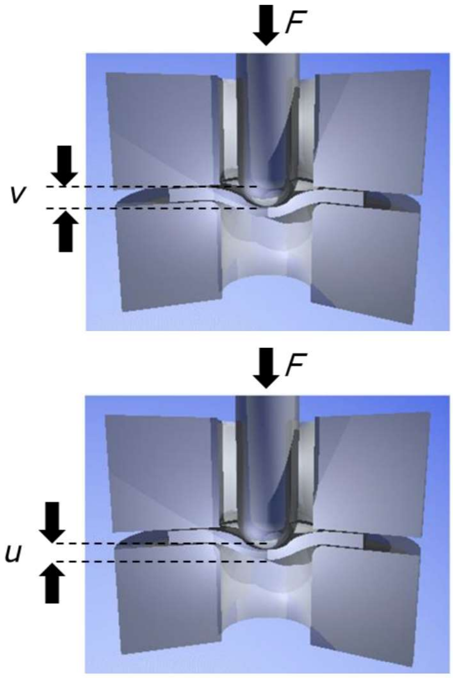
SLM materials and SP deformation definitions



SLM280

SLM500

Machine / run	Charpy direction	SP plane	HT
SLM280 / 60	XY	XY	No HT
SLM280 / 60	XY	XY	2h/950°C/air cool
SLM280 / 57	Z	Z	No HT
SLM280 / 57	Z	Z	2h/950°C/air cool
SLM500 / 53	XY	XY	No HT
SLM500 / 53	XY	XY	2h/950°C/air cool
SLM500 /50	Z	Z	No HT
SLM500 / 50	Z	Z	2h/950°C/air cool



v = displacement , from top of specimen to puncher tip (do be compliance corr.)
u= deflection measured from below (no compliance)

European SP standards documents

- CWA 15627 (rev. 2007)
  - CEN deliverable
  - Pre-normative document
  - Limited lifetime
  - SP and SPC

- **Draft standard by ECISS/TC 101/WG 1 (WI=EC101162) 2017-2018**
  - (to become *EN-15627*)
  - Apparatus, procedures
    - 8 mm and 3 mm specimens
  - Estimation of tensile/fracture properties
  - Estimation of creep properties
  - Data formats

ECISS/TC 101

Date: 2017-12-12

TC 101 WI

ECISS/TC 101

Secretariat: AFNOR

“Metallic materials - Small punch test method”

Einführendes Element — Haupt-Element — Ergänzendes Element

Élément introductif — Élément central — Élément complémentaire

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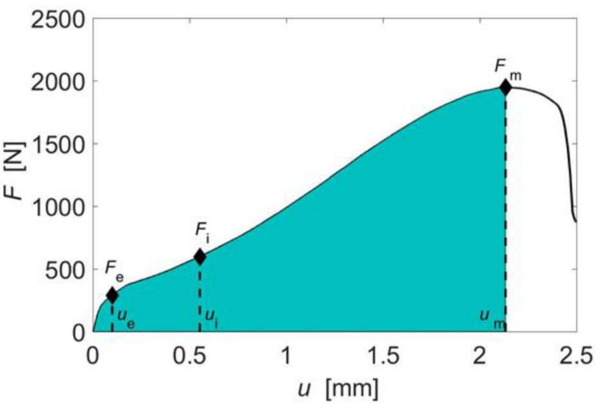
Principle of SP and SPC

Small Punch (SP)

$\dot{w}$ = const.



TC 101 WI

Annex C
(informative)

Estimation of ultimate tensile strength R_m from small punch testing

C.1 General approach

The small punch test can be used to estimate ultimate tensile stress, R_m determined by a standardized uniaxial tensile test. Two correlations were proposed for the estimation of R_m [5]-[9]:

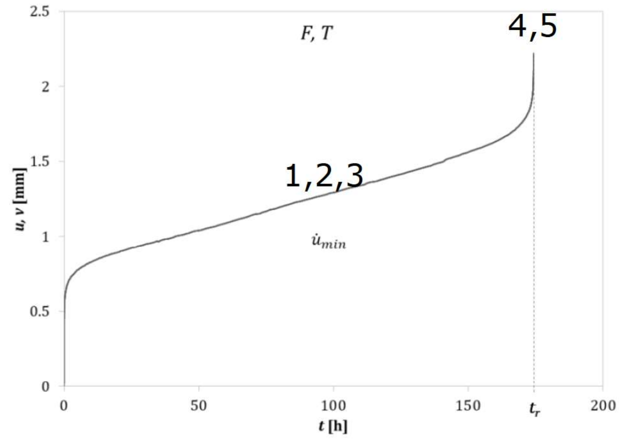
$$R_m = \beta_{Rm} \cdot F_m / (h_0 \cdot u_m) \quad [C.1]$$

$$R_m = \beta_{Rm} \cdot F_i / h_0^2 \quad [C.2]$$

NOTE β_{Rm} in equation C.1 and C.2 do not have the same value. For details refer to Clauses C.2 and C.3.

Small Punch Creep (SPC)

F = const.



(informative)

Estimation of creep properties from small punch creep testing

G.1 General approach

$$\Psi = \frac{F}{\sigma} = 1{,}916 \cdot u_{\min}^{0{,}6579} \text{ (N/MPa)}$$

1. Minimum deflection rate (mm/h)
2. Time to minimum deflection rate (h)
3. Total deflection at minimum deflection rate (mm)

4. Time to failure (h)
5. Total deflection at failure (mm)

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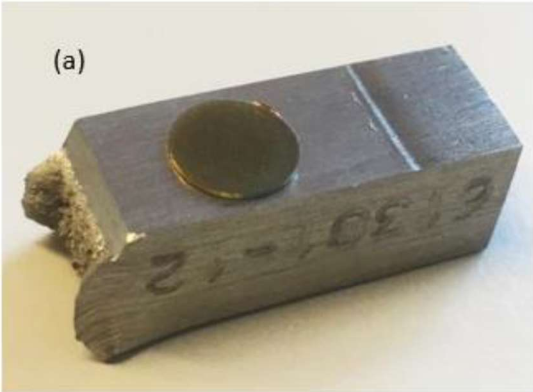
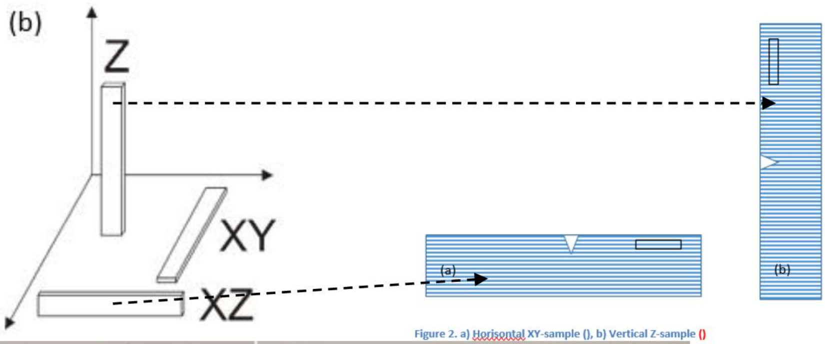
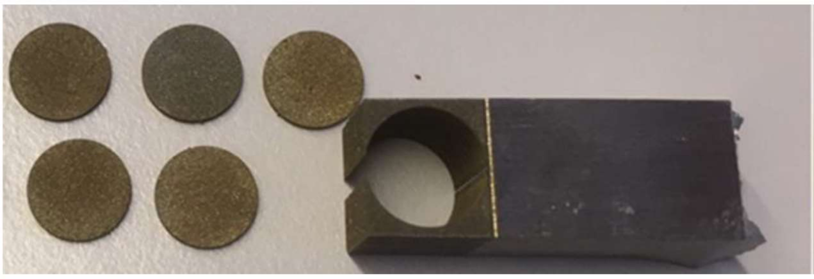
316L SLM small punch samples extracted from ½ a Charpy specimen (10 pcs / material)



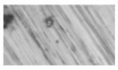
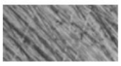
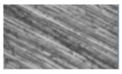
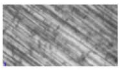
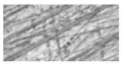
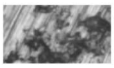


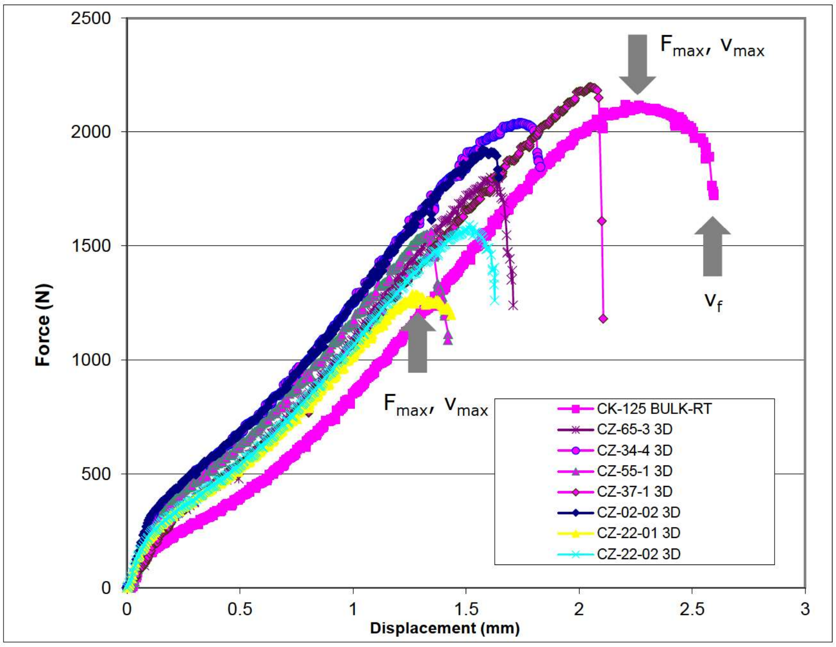


- 2 printing machines, 2 directions of SP specimen extraction, 2 heat treatments

NOTE: the SP/SPC test is a <u>biaxial-test</u> (PLANE Z test)
BOTH the Z and XY directions are tested

Hardness (HV05) and SP tests (room temp.)

Specimen	Charpy direction / Heat treatment	HV (0.5)	Surface
316L BULK	N/A	137±5	
CZ-12	XY / NO	200±9	
CZ-22	XY / YES	174±12	
CZ-02	Z / NO	186±8	
CZ-05	Z / YES	172±5	
CZ-55	XY/ NO	204±8	
CZ-65	XY / YES	174±9	
CZ-34	Z /NO	210±10	
CZ-37	Z /YES	174±8	



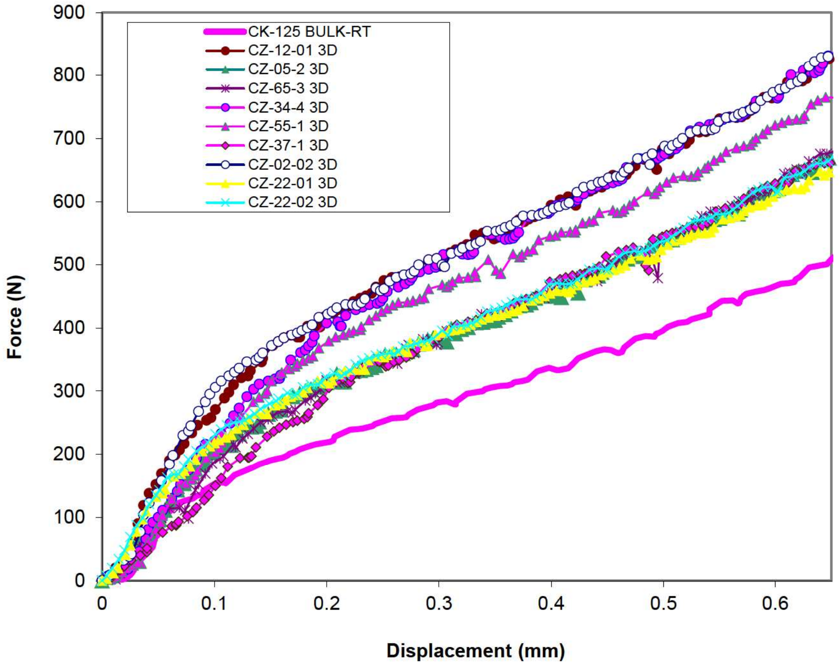
- The maximum force (F_{max}) and the displacement at the maximum force (v_{max}) is used for tensile strength estimation R'_m

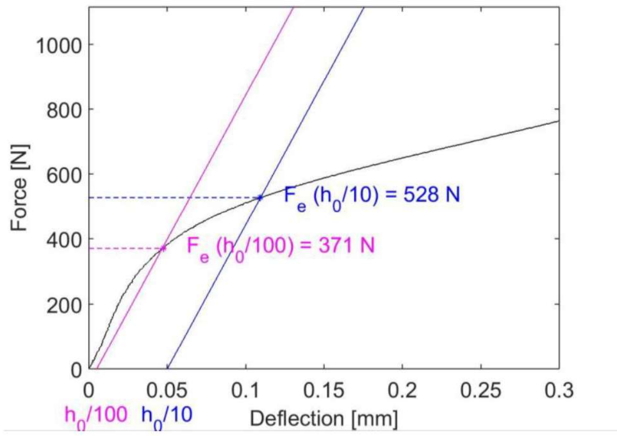
- The displacement at fracture (v_f) can be used as a measure of ductility

HV 0.5 kg, 15s, 6 repetitions

SP tests conducted at displacement rate of 0.5 mm / min

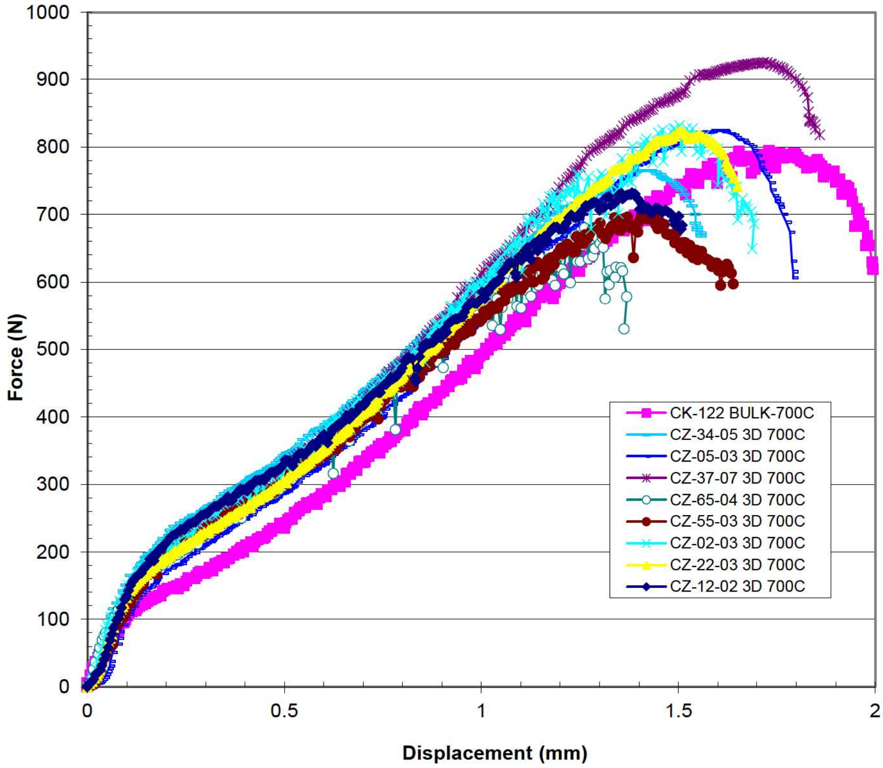
Beginning of the force-deflection curves (RT)

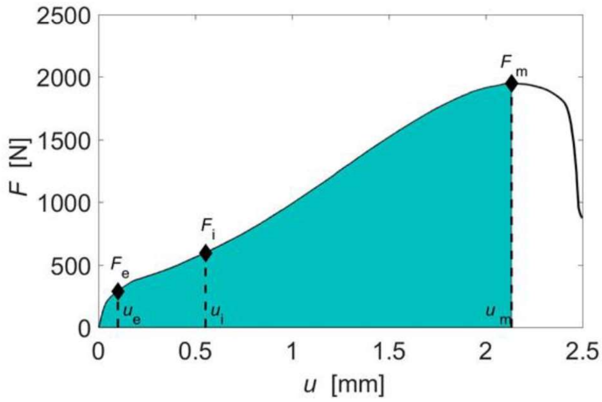




Offset method (0.05 mm) used for defining F_e and estimating proof strength R_p.

SP tests conducted at 700° C





For estimating R_m at 700° C,
Support for SPC creep tests (initial deflection after test start)

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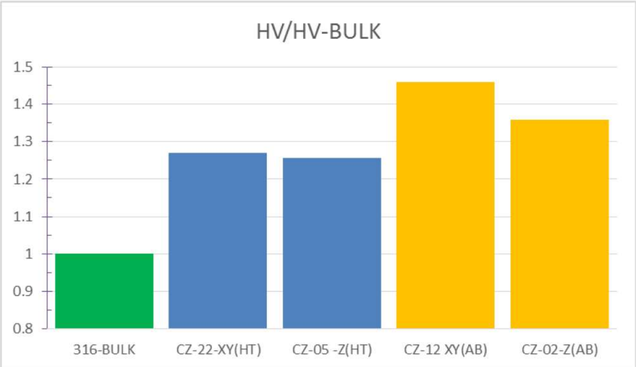
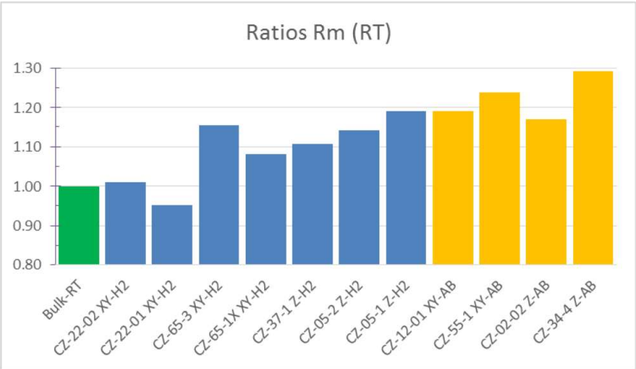
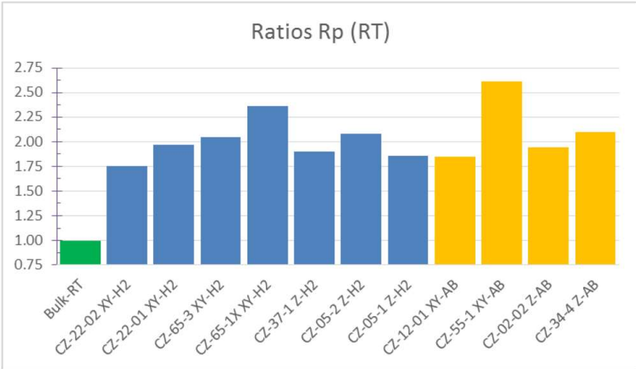
Estimated R_m and R_p (RT, relative to 316L bulk)



The sample hardness tests shows:

HV-AB > HV-HT> HV-BULK





SP: (in average) the AB material estimates for R_m is 123±5% and R_p 222±29% of the bulk

For the heat treated (HT) material the estimated R_m is 109±8% and R_p is 200±18%

SP has least sensitivity to R_p estimation (largest scatter)

The HT lowers both R_m and R_p by about 10% and improves ductility

SPC creep test examples

Required test parameters:

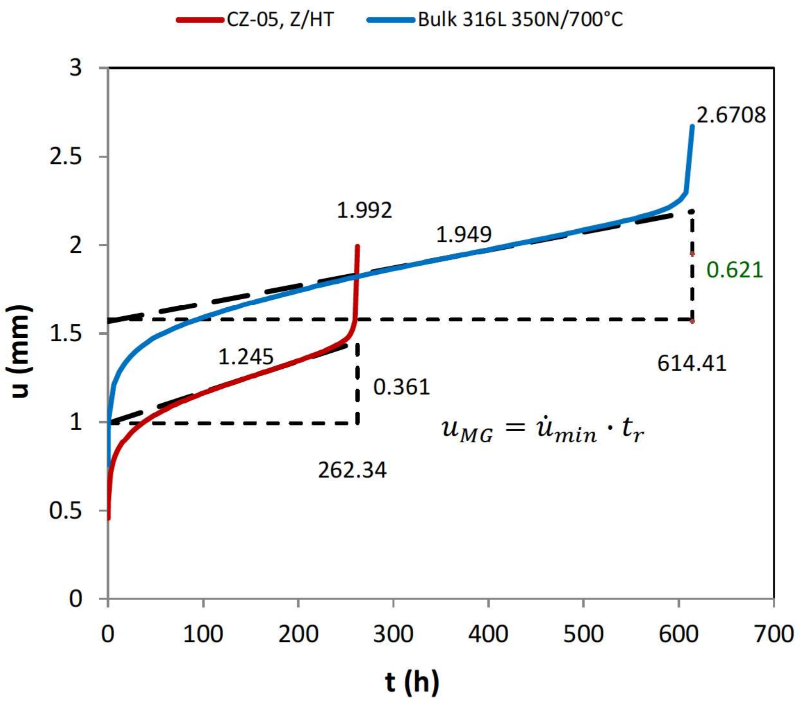
Test specification:

I. Temperature (°C)
II. Load (N)

TO BE MEASURED:

- Time to:
  I. Minimum deflection rate
  II. Failure

- Deflection at:
  I. Before loading (at temp.)
  II. Loaded
  III. Minimum deflection rate
  IV. Failure



NOTE: The equivalent stress is NOT the same even though the force is,

$$\Psi = \frac{F}{\sigma} = 1{,}916 \cdot u_{\min}^{0{,}6579}\ (\mathrm{N/MPa})$$

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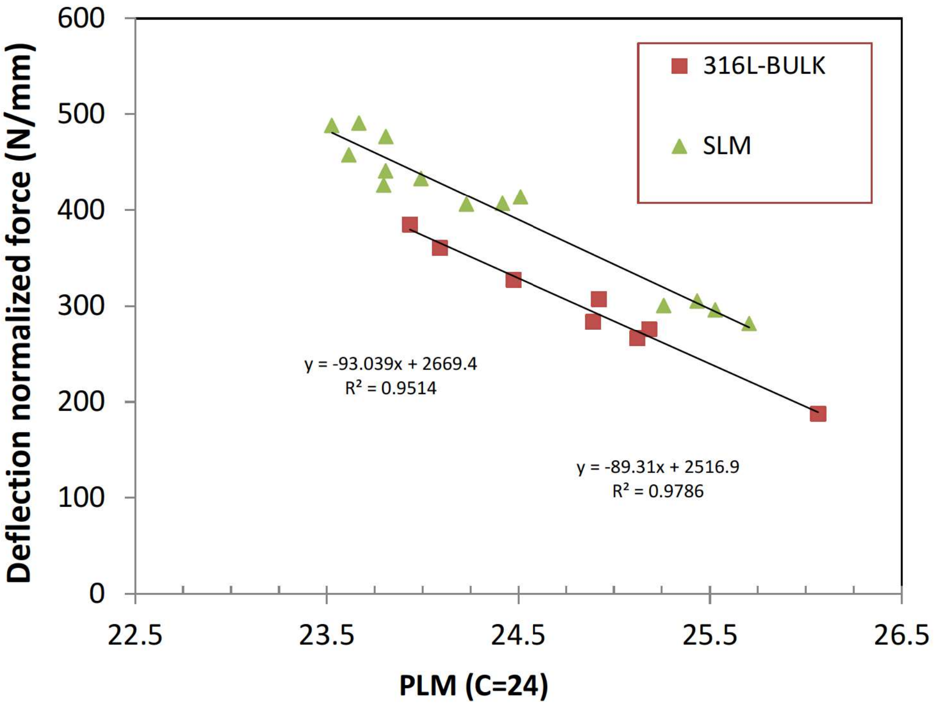
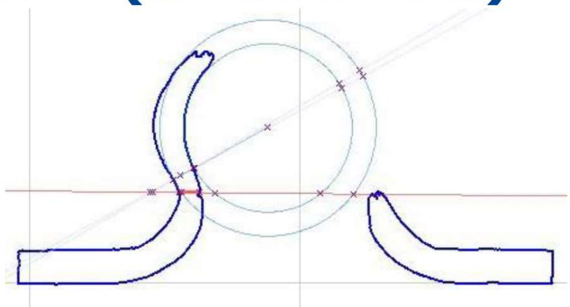
Creep strength in comparison to bulk material



The <u>initial</u> assessment of the SLM (short duration) creep properties indicate that SLM-316L is 15% stronger than the 316L bulk steel.

NOTE : the deflection normalized force is NOT equivalent to equivalent stress (in the standard) test showing early cracking cannot be assessed as above.

Challenges regarding DUCTILITY (SP and SPC)



Ductility estimates from SP and SPC by test data assessment or by post-test examination

SP test data:

Extracting the displacement at maximum force $v_{max} = v(F_{max})$

- low v_{max} ⇨ low ductility

SPC test data:

Use deflection at minimum deflection rate and Monkman-Grant deflection, $u_{MG} = \dot{u}_{min} \cdot t_r$

- low $u(\dot{u}_{min})$ and low u_{MG} ⇨ low ductility

Post test examination (both SP and SPC)

- "Minimum" wall thickness h_f (difficult)
- Other descriptors;
  - Interrupted testing; SPS at 1/2 tr, SP at 80% F_{max}
  - Average wall thickness h_a at specified hight

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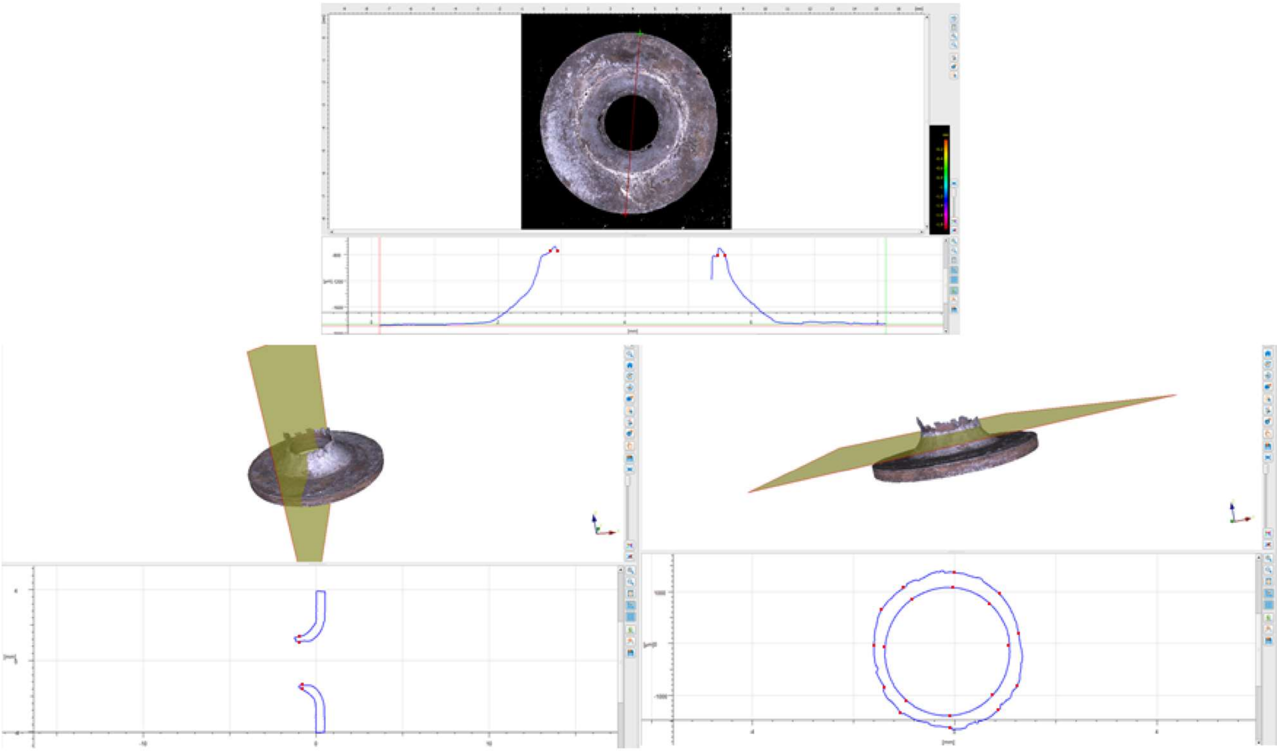
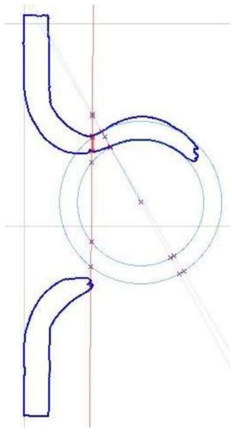
Post test evaluation (1)



Using Alicona 3D profilometer
TOP scan (a few minutes) vs full 3D scan by rotation unit (7-10 h)

Post test examination (CZ-12) for cross checking with estimated creep stress



Measured “minimum wall thickness” = ZZZ mm (from ligament)

Measured contact surface = YYY mm (from HAT)

Calculated contact pressure at failure= XXX MPa (from HAT)

Conclusions

Tensile properties

- SP is clearly suitable for estimating tensile strength of 3D material
- Proof strength is more complicated and has larger scatter

Creep properties

- SPC has been shown to give reliable estimates on short term creep strength (new standard, round robin on several steels)
- For SLM 316L the SPC results indicate good creep strength in the same order (or up to 15% better) than bulk 316L material

Ductility

- The material ductility influences both SP and SPC estimates
- Cracking in SP and SPC test can be difficult to detect and are not taken into account in the simplified correlations of the standard

Ongoing work

- Detailed in-depth assessment of the SP and SPC data presented here
- Simulation by FEA ongoing to improve estimates for semi ductile and brittle materials

Acknowledgements

JRC wishes to Acknowledge the ECCC (WG1, 3A and 3B) for the interest and support in the development of the miniature testing techniques SP and SPC.