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ALIGNMENT TILT AND FORCE TRANSDUCER CREEP EFFECTS ON HARDNESS IN CONVENTIONAL HARDNESS TESTS / Fidelus, J. D.; Bejma, D.; Prato, A.; Germak, A.. - (2023), pp. 1-6. [10.21014/tc5-2022.104]

IMEKO 24th TC3, 14th TC5, 6th TC16 and 5th TC22 International Conference
11 – 13 October 2022, Cavtat-Dubrovnik, Croatia

ALIGNMENT TILT AND FORCE TRANSDUCER CREEP EFFECTS ON HARDNESS IN CONVENTIONAL HARDNESS TESTS

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Abstract:
This paper describes the investigations of alignment effects and the influence of force transducer creep in conventional hardness tests performed on GUM's deadweight-type Rockwell Hardness Standard Machine (HSM), Vickers Hardness Machine (HM), Brinell HM and INRiM's Primary Hardness Standard Machine (PHSM).

Keywords: hardness; Rockwell; Vickers; Brinell; alignment effects; force transducer creep

1. INTRODUCTION

In practice, the various systems work far from perfect conditions such as constant temperature and uniaxial forces, and there are additional effects due to hysteresis, alignment and non-axial force application. Meanwhile the currently available traceability chain covers only uniaxial static forces, applied perfectly, at constant temperature, to test specimens that react in a purely axisymmetric manner. This is why it is necessary to investigate the influences of these effects on the measurement results obtained from a range of materials tests [1]. The Rockwell hardness (HR) test method is very well suited for measuring hard products and some hardened layers. The advantages of this method are speed and ease of measurement as well as simple operation of the machine, making it suitable for automation. However, its major disadvantage is the very large impact of incorrect object positioning on the measurement result. The presented work concerns research on a traceability chain for continuous force measurement for metrological services in the fields of material testing and other mechanical test facilities carried out in the EMPIR 18SIB08 ComTraForce project [1]. This paper covers research on the impact of alignment tilt and force transducer creep on test results for Rockwell, Vickers, and Brinell hardness.

2. ALIGNMENT TILT EFFECTS

2.1. Measurement Method

Hardness machines

A study of alignment tilt effects on hardness testing was performed in GUM's modernised deadweight-type Rockwell HSM [2], [3], Vickers HM and Brinell HM (Figure 1).

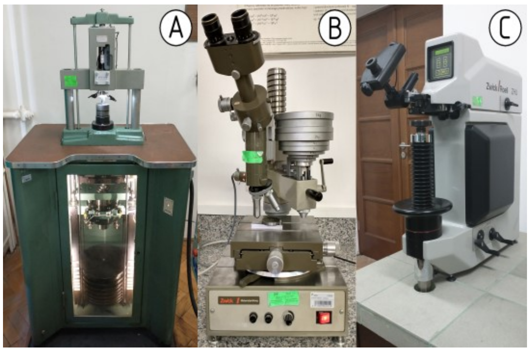

Figure 1: GUM's Hardness Machines used during tilt alignment tests: A) Rockwell HSM; B) Vickers HM; C) Brinell HM

Hardness standard blocks

Hardness standard blocks of 20 HRC, 65 HRC, 160 HV10, 430 HV10, 200 HBW2.5/187.5, and 380 HBW2.5/187.5 were used in these tests. Standard testing cycle according to EN ISO 6508-3 [4] was used in all Rockwell measurements.

Angled blocks

Angled blocks of 0.25°, 0.5°, 1°, 2° and 5° were used to obtain correct angling of the hardness blocks (Figure 2).

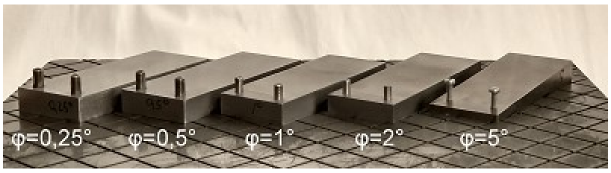

Figure 2: Blocks with different angles

The arrangement of the hardness block on the angled block is depicted in Figure 3.

Figure 3: Arrangement of the hardness block on the angled block

There is no need to fix blocks to the specimen support surface of HSM because friction force between the block and the support is sufficient to prevent horizontal motion. In order to prove this let's assume there is no friction between the indenter and the angled surface of the hardness block – this is the most inconvenient case because in reality there is also force between the indenter and the angled surface of the hardness block (Figure 4), but due to deformation of surface it's difficult to estimate its value.

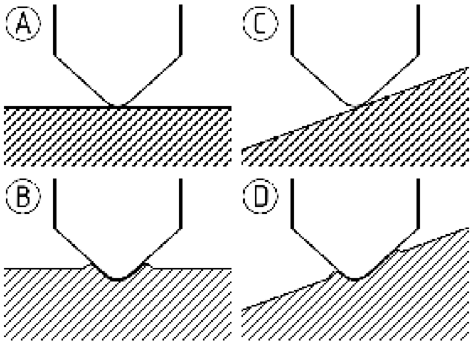

Figure 4: Interaction between the indenter and: flat surface (A, B)/angled surface (C, D)

Diagram (Figure 5) shows forces applied to the angled block during hardness testing in case of zero indenter-surface friction.

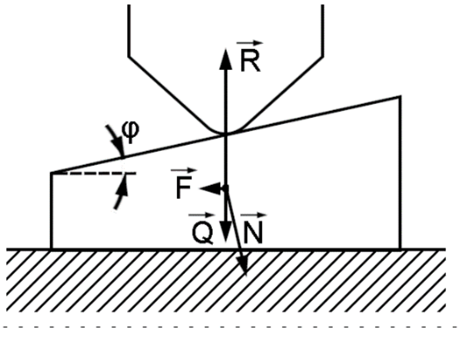

Figure 5: Distribution of forces on the interface of the indenter and hardness block (a case of zero indenter-surface friction)

where:

φ – angle of the block
N – force applied by the indenter
R – reaction force from a support below the block
Q – weight of the block
F – friction between the block and the support

Conditions for static equilibrium are:

$$N\sin\varphi - F = 0 \tag{1}$$

$$R - Q - N\cos\varphi = 0\,. \tag{2}$$

Friction force cannot exceed value of:

$$F \leq \mu R\,, \tag{3}$$

where μ is the frictional coefficient for steel on steel, assumed to be greater than 0.15.

$$\mu R \geq N\sin\varphi\,. \tag{4}$$

In conducted experiments all forces exerted by indenters were greater than 100 N while weights of stacked blocks didn't exceed 4 N and so we can neglect weight of blocks obtaining:

$$R - N\cos\varphi = 0\,. \tag{5}$$

This leads us to expression for the maximal safe angle:

$$\tan\varphi \leq \mu\,. \tag{6}$$

For assumed friction coefficient of 0.15 the maximal safe angle is 8.5°. Greater tilt can lead to failure of the hardness machine.

2.2. Measurement results and discussion

Alignment tilt effects on Rockwell hardness

The research was carried out for the Rockwell C scale - the most popular of the 30 Rockwell scales defined by ASTM (ISO defines 15 of these) [5]. The Rockwell test is one step process in which hardness is obtained as a function of intender displacement according to EN ISO 6508-3. Its major disadvantage is the very large impact of incorrect item setting / hardness block on the measurement result. Given that 1 HRC corresponds to 2 µm, the measurement of the permanent depth increment has a great influence on the accuracy of the hardness measurement and is a significant component of the measurement uncertainty budget.

The hardness standard blocks of 65 HRC and 20 HRC were tested in minus (-) and plus (+) planes i.e. with tilt angle range of -5°, -2°, -1°, 0°, 1°, 2° and 5° (Figure 6).

Figure 6: A study of alignment effects on GUM's Rockwell hardness standard machine

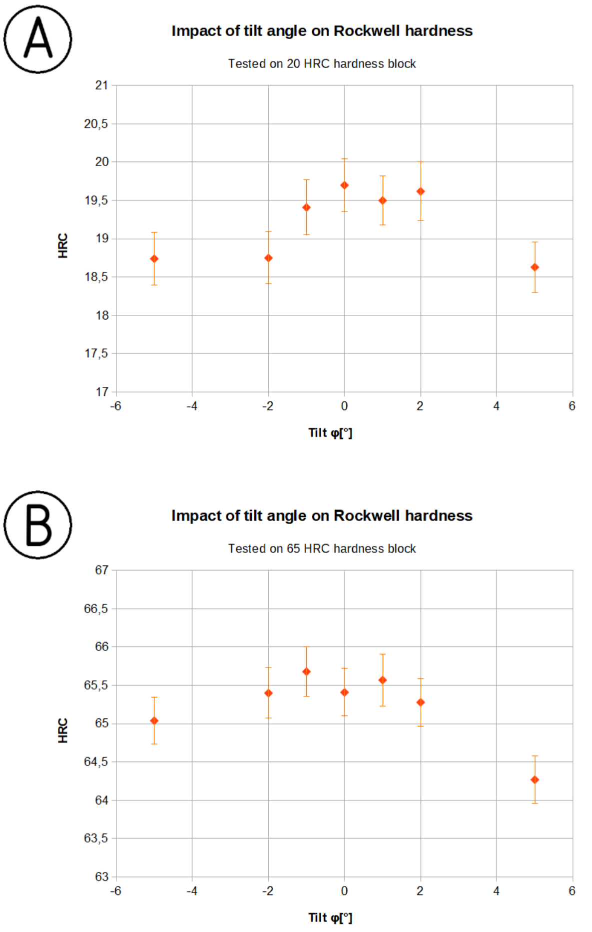

Figure 7: Impact of tilt angle on Rockwell hardness A) 20 HRC hardness standard block; B) 65 HRC hardness standard block

For the softer block (Figure 7A), a decrease in hardness of 0.4 HRC is observed at tilt angles of ± 1°, however these values are still within the error limits. A clear decrease in hardness (about 1 HRC) occurs at tilt angles of -2° and ± 5°. For the harder block (Figure 7B), a slight decrease in hardness at a tilt angle of 2° and a clear decrease in hardness (approx. 1 HRC) at one of 5° can be observed.

Alignment tilt effects on Vickers and Brinell hardness tests

The Vickers and Brinell hardness tests are performed in a two-step process where the sample is first indented and then a geometrical characteristic of the imprint is measured by microscope, either within the machine or external to it. The tilt angle of the tested surface can therefore be different on hardness machine and under the microscope so the angle of observation should be taken into consideration (Figure 8), although it can be demonstrated mathematically that, for small angles, the change in observed dimension is negligible. Taking d_0 as the measured diameter when the surface of the hardness block is perpendicular to the optical axis of microscope and d_φ as the diameter when the block is tilted by angle φ, we have:

$$d_\varphi = d_0 \cos\varphi\,. \qquad (7)$$

Since tilt is less than 5°, the difference between d_0 and d_φ is smaller than 0.4 %. Such a small difference is unimportant and not visible in microscopic photos, although it can lead to focussing difficulties due to the height differences.

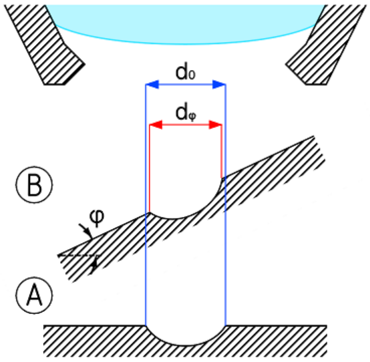

Figure 8: Dependence of geometric dimensions on the observation angle: A) observed imprint is on a flat surface; B) observed imprint is on a tilted surface

The above theoretical considerations have been experimentally verified. Hardness tests (Vickers and Brinell) were carried out at angles of 0.25°, 0.5 °, 1°, 2° and 5°. Figure 9 shows the impact of tilt angle on Vickers hardness. The results are presented for both at flat top and at angle of φ observations. For both the soft (Figure 9A) and hard (Figure 9B) samples, no impact of tilt angle up to 2° on hardness was observed. A slight decrease in hardness can be seen for the tilt angle of 5°, but the hardness results are in the error range of the measurement.

Figure 10 shows the Vickers indentations seen both horizontally and angled to the optical axis of microscope. Only for angles greater than 2° can a slight change in shape be seen. A study on Brinell hardness tests performed for identical tilt angles showed similar results. No significant changes in geometry (Figure 11) or hardness (Figure 12) can be observed.

3. INFLUENCE OF FORCE TRANSDUCER CREEP

Influence of force transducer creep on hardness in Rockwell, Vickers and Brinell tests were carried out on the INRiM Primary Hardness Standard Machine (Figure 13).

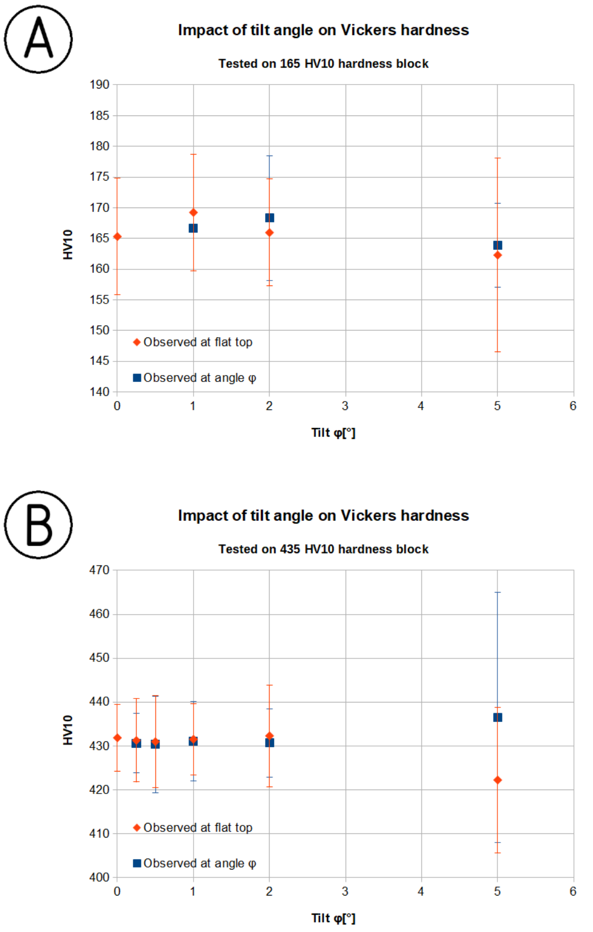

Figure 9: Impact of tilt angle on Vickers hardness. Tested on A) 165 HV10 hardness standard block; B) 435 HV10 hardness standard block

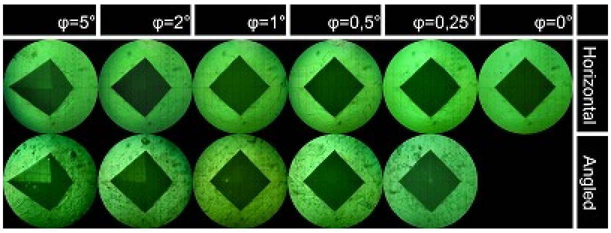

Figure 10: Imprints seen horizontally and angled to optical axis of microscope. Vickers hardness tests on 435 HV10 hardness standard block

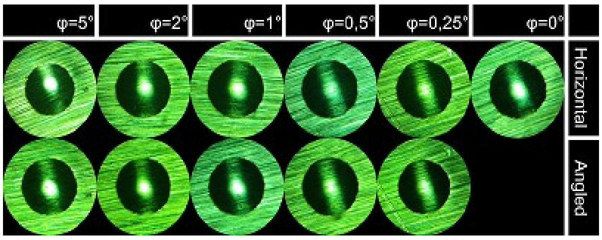

Figure 11: Imprints seen horizontally and angled to optical axis of microscope. Brinell hardness tests on 365 HBW2.5 / 187.5 hardness standard block

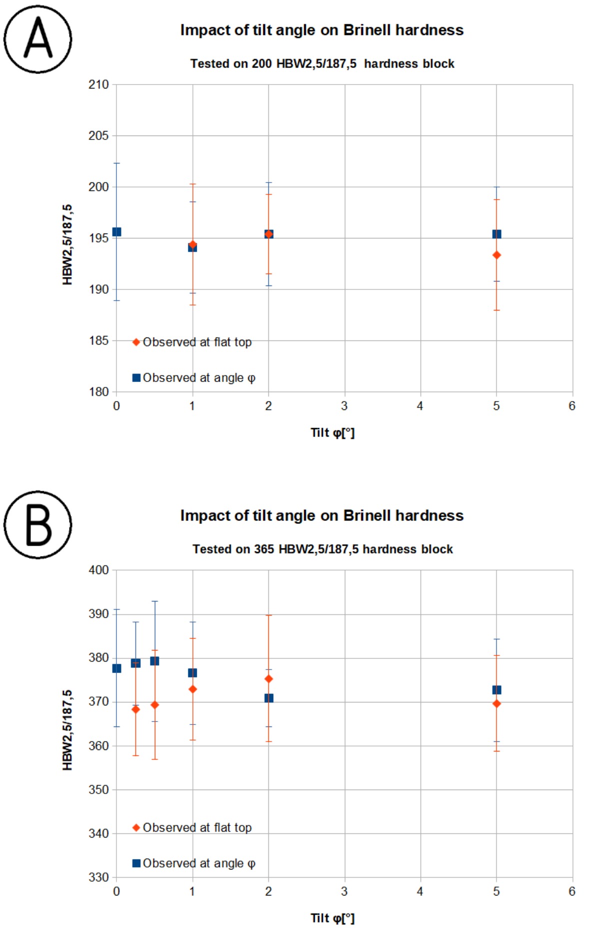

Figure 12: Impact of tilt angle on Brinell hardness. Tested on A) 200 HBW2.5 / 187.5 hardness standard block; B) 365 HBW2.5 / 187.5 hardness standard block

Figure 13: Primary Hardness Standard Machine at INRiM

A typical industrial durometer for the measurement of Rockwell Hardness uses a force transducer to monitor the application of the preliminary test force and the final load. The duration of these forces is given in specific ranges, which are 1 s to 4 s and 2 s to 6 s, respectively. However, force transducers are subjected to creep recovery during the maintenance of the load, therefore the force is perfectly constant during this period of time. This behaviour directly influences the HR results, in particular during the maintenance of the final load. Such influence can be experimentally evaluated in terms of sensitivity coefficients (in HR/N). Such coefficients, multiplied by the force variation due to the creep of the force transducer, provide the variation of HR which, in this way, can be corrected. In literature, these coefficients have been derived for the different HR scales for different hardness levels [6]-[13]. As an example, preload and final load influences in HRC at different hardness levels (25 HRC, 40 HRC and 60 HRC) were previously evaluated using the INRiM PHSM with different combinations of preloads and final loads in order to have a full factorial experimental plan, which guarantees more accurate results and lower uncertainties, as shown in Figure 14.

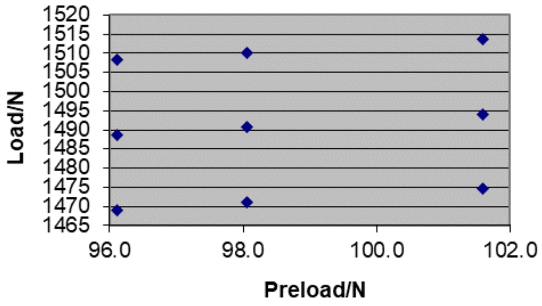

Figure 14: Experimental plan to evaluate the influence of creep in HRC at INRiM

By way of example, the HRC variation found as function of the preload and final load for the 60 HRC block is reported in Figure 15. Results for all blocks are summarised in Figure 16 and Figure 17.

Performing the regression of these curves, a sensitivity coefficient for each hardness level and each hardness scale is obtained. These values are reported in the above-mentioned literature. Using these coefficients and supposing, as a cautious esteem, a creep of 0.03 % of a typical force transducer during the final load maintenance (which changes from scale to scale), the variation of hardness values can be evaluated for different hardness levels and each hardness scale.

In general terms, it is found the variation in Rockwell hardness is always negative and decreases at increasing hardness levels. By way of example, the results for HRBW Rockwell scale are reported in Table 1.

Table 1: HRBW Rockwell hardness variations due to creep at different hardness levels

HRBW level	Final force / N	Sens. coeff. / HRB/N	Creep / N	Variation / HRB
10	980.7	-0.14	0.294 21	-0.041
40	980.7	-0.1	0.294 21	-0.029
70	980.7	-0.07	0.294 21	-0.021
100	980.7	-0.04	0.294 21	-0.012

Due to the impossibility of reporting all results for all Rockwell scales, the highest hardness variations due to force transducer creep during final load application are summarised for the different scales in Table 2. It is found that variations are low compared to a typical Rockwell hardness uncertainty in the order of 0.1 HR.

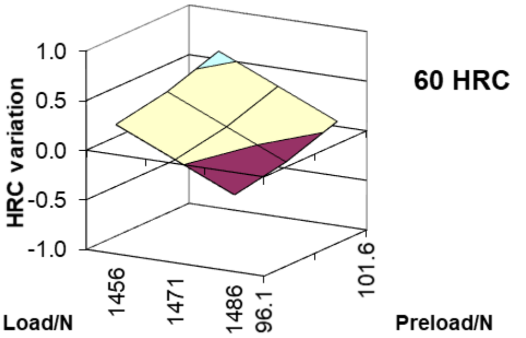

Figure 15: HRC variation as function of the preload and the load on the 60 HRC block

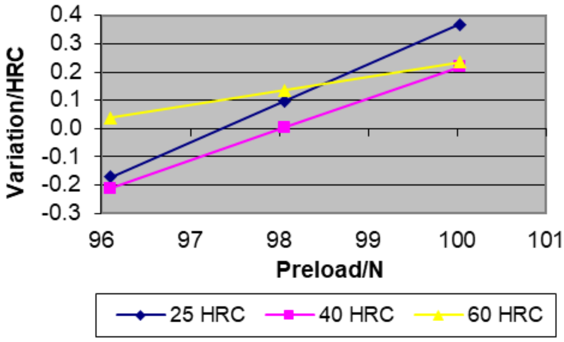

Figure 16: HRC variation as function of the preload

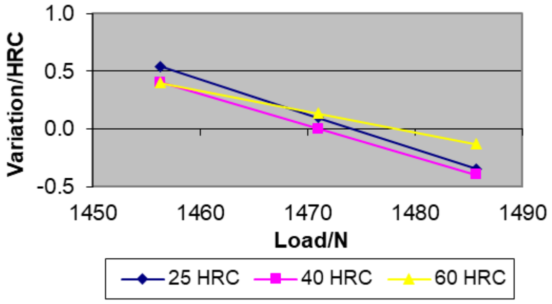

Figure 17: HRC variation as function of the load

Table 2: Highest hardness variations due to creep for different Rockwell Hardness scales.

Scale	Final force / N	variation / HR
HR15N	147.1	-0.01
HR30N	294.2	-0.01
HR45N	441.3	-0.01
HRA	588.4	-0.03
HRC	1471	-0.02
HRD	980.7	-0.01
HRGW	1471	-0.04
HRBW	980.7	-0.04
HR45TW	441.3	-0.03
HR30TW	294.2	-0.02
HR15TW	147.1	-0.01
HRFW	588.4	-0.02

The same procedure has been performed for Brinell and Vickers hardness at different scales and hardness levels. The only difference is that a higher creep is cautiously estimated, i.e. equal to 0.05 % due to longer load maintenance duration.

In general terms, variations are always negative, but do not follow a linear trend as a function of the hardness level, as for Rockwell hardness. However, the highest relative variations are summarised in Table 3 and Table 4.

Table 3: Highest hardness relative variations due to creep for different Brinell scales.

Scale	Force / N	Max rel. variation / %
HBW1/30	294.2	-0.07
HBW2.5/187.5	1 839	-0.07
HBW5/750	7 355	-0.48
HBW10/3000	29 420	-0.55

Table 4: Highest hardness relative variations due to creep for different Vickers scales.

Scale	Force / N	Max rel. variation / %
HV0.1	0.98	-0.06
HV1	9.81	-0.06
HV10	98.1	-0.06
HV100	981	-0.06

4. SUMMARY

The study of alignment effects on hardness in conventional hardness tests were performed on GUM's and INRiM's (PHSM) hardness machines.

Investigations of hardness block tilt angle up to 5° on the hardness results for Rockwell (HRC), Vickers (HV10) and Brinell (HBW2.5 / 187.5) methods were performed. A decrease in hardness of about 1 HRC at a tilt angle of - 2° and ± 5° for 19.7 HRC hardness standard block was found. For Vickers and Brinell hardness, no influence of tilt angle on the test results was observed.

The influence of force transducer creep on hardness in conventional hardness tests was determined.

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6. ACKNOWLEDGEMENT

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

This work is part of the 18SIB08 project with acronym ComTraForce funded by the EMPIR programme. One of the authors (J. D. F.) thanks A. Knott from NPL for openness, fruitful discussions and valuable advice