COOMET Rockwell PTB/KazInMetr comparison

Final report

Braunschweig, November 2008/ K. Herrmann
Karaganda, November 2008/ M. Zhamanbalin
1 Introduction
This bilateral comparison of Rockwell scales between Kazakhstan Institute of Metrology (abbreviated as KazInMetr) was agreed upon in the year 2006 in the COOMET theme 371/KZ/06, in which should participate the hardness laboratories of national metrology institutes of Germany (PTB) and Kazakhstan (KazInMetr). The Physikalisch-Technische Bundesanstalt Braunschweig (Germany) declared the readiness to act as pilot laboratory of the comparison.

2 Organization
Participants
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Time schedule of the comparison
The comparison started in August 2007 with the measurements at PTB. The following table shows the scheduled measuring time:

<table>
<thead>
<tr>
<th>Institute/country</th>
<th>Time of measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>PTB, Germany</td>
<td>08/2007</td>
</tr>
<tr>
<td>KazInMetr, Kazakhstan</td>
<td>05/2008</td>
</tr>
</tbody>
</table>

3 Standards

3.1 Description
In the bilateral comparison 8 sets for the Rockwell scales HRC, HRA, HRB, HR15N, HR30N, HR45N, HR15T, HR30T with each 3 different hardness levels are used, that is altogether 24 blocks. The blocks are triangular with an edge length of 70 mm x 70 mm x 70 mm and a thickness of 6 mm. The upper side of the blocks which is the measurement surface is finished. The blocks are manufactured as commercial products by Buderus Co., Germany.

3.2 Handling
It is recommended to clean the blocks after unpacking with alcohol and then sign the measurement locations with a fiber pen. After measurement all dots on the blocks must be removed before packing in order to avoid corrosion.

4 Measurand
The measurand is the hardness value in five locations on a hardness reference block. The procedure of the hardness measurement is defined in ISO 6508-1 and -3.

5 Methods of measurement
6 Measurement results
In the following table the results for the hardness reference blocks are summarized. The results are expressed by the mean values of each 5 indentations in Table 1.

Table 1: Mean values of the hardness measurement results (in HR)

<table>
<thead>
<tr>
<th>Hardness scale</th>
<th>( H_{\text{PTB}} )</th>
<th>( U_{\text{PTB}} )</th>
<th>( H_{\text{KazInMetr}} )</th>
<th>( U_{\text{KazInMetr}} )</th>
<th>( \Delta(\text{KazInMetr}-\text{PTB}) )</th>
<th>( \Delta_{\text{acceptable}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>60 HRA</td>
<td>59.84</td>
<td>0.3</td>
<td>59.90</td>
<td>0.5</td>
<td>+0.06</td>
<td>0.58</td>
</tr>
<tr>
<td>70 HRA</td>
<td>71.33</td>
<td>0.3</td>
<td>71.10</td>
<td>0.5</td>
<td>-0.23</td>
<td>0.58</td>
</tr>
<tr>
<td>80 HRA</td>
<td>81.36</td>
<td>0.3</td>
<td>81.26</td>
<td>0.5</td>
<td>-0.10</td>
<td>0.58</td>
</tr>
<tr>
<td>60 HRB</td>
<td>59.03</td>
<td>0.5</td>
<td>58.36</td>
<td>0.8</td>
<td>-0.67</td>
<td>0.94</td>
</tr>
<tr>
<td>75 HRB</td>
<td>75.76</td>
<td>0.5</td>
<td>75.08</td>
<td>0.8</td>
<td>-0.68</td>
<td>0.94</td>
</tr>
<tr>
<td>100 HRB</td>
<td>97.64</td>
<td>0.5</td>
<td>97.04</td>
<td>0.8</td>
<td>-0.60</td>
<td>0.94</td>
</tr>
<tr>
<td>30 HRC</td>
<td>29.34</td>
<td>0.3</td>
<td>29.36</td>
<td>0.5</td>
<td>+0.02</td>
<td>0.58</td>
</tr>
<tr>
<td>50 HRC</td>
<td>49.84</td>
<td>0.3</td>
<td>49.71</td>
<td>0.5</td>
<td>-0.13</td>
<td>0.58</td>
</tr>
<tr>
<td>65 HRC</td>
<td>62.79</td>
<td>0.3</td>
<td>62.76</td>
<td>0.5</td>
<td>-0.03</td>
<td>0.58</td>
</tr>
<tr>
<td>70HR15N</td>
<td>71.00</td>
<td>0.4</td>
<td>70.85</td>
<td>0.7</td>
<td>-0.15</td>
<td>0.81</td>
</tr>
<tr>
<td>80HR15N</td>
<td>81.73</td>
<td>0.4</td>
<td>81.35</td>
<td>0.7</td>
<td>-0.38</td>
<td>0.81</td>
</tr>
<tr>
<td>90HR15N</td>
<td>89.87</td>
<td>0.4</td>
<td>89.83</td>
<td>0.7</td>
<td>-0.04</td>
<td>0.81</td>
</tr>
<tr>
<td>50HR30N</td>
<td>49.44</td>
<td>0.4</td>
<td>49.46</td>
<td>0.7</td>
<td>+0.02</td>
<td>0.81</td>
</tr>
<tr>
<td>60HR30N</td>
<td>60.93</td>
<td>0.4</td>
<td>60.47</td>
<td>0.7</td>
<td>-0.46</td>
<td>0.81</td>
</tr>
<tr>
<td>75HR30N</td>
<td>76.23</td>
<td>0.4</td>
<td>75.86</td>
<td>0.7</td>
<td>-0.37</td>
<td>0.81</td>
</tr>
<tr>
<td>30HR45N</td>
<td>31.17</td>
<td>0.4</td>
<td>31.03</td>
<td>0.7</td>
<td>-0.14</td>
<td>0.81</td>
</tr>
<tr>
<td>50HR45N</td>
<td>49.70</td>
<td>0.4</td>
<td>49.32</td>
<td>0.7</td>
<td>-0.38</td>
<td>0.81</td>
</tr>
<tr>
<td>65HR45N</td>
<td>65.13</td>
<td>0.4</td>
<td>65.15</td>
<td>0.7</td>
<td>+0.02</td>
<td>0.81</td>
</tr>
<tr>
<td>80HR15T</td>
<td>79.38</td>
<td>0.8</td>
<td>79.60</td>
<td>0.8</td>
<td>+0.22</td>
<td>1.13</td>
</tr>
<tr>
<td>85HR15T</td>
<td>83.80</td>
<td>0.8</td>
<td>84.02</td>
<td>0.8</td>
<td>+0.22</td>
<td>1.13</td>
</tr>
<tr>
<td>90HR15T</td>
<td>90.27</td>
<td>0.8</td>
<td>90.22</td>
<td>0.8</td>
<td>-0.05</td>
<td>1.13</td>
</tr>
<tr>
<td>55HR30T</td>
<td>54.62</td>
<td>0.8</td>
<td>55.50</td>
<td>1.2</td>
<td>+0.88</td>
<td>1.44</td>
</tr>
<tr>
<td>65HR30T</td>
<td>64.72</td>
<td>0.8</td>
<td>65.57</td>
<td>1.2</td>
<td>+0.85</td>
<td>1.44</td>
</tr>
<tr>
<td>80HR30T</td>
<td>78.34</td>
<td>0.8</td>
<td>78.88</td>
<td>1.2</td>
<td>+0.54</td>
<td>1.44</td>
</tr>
</tbody>
</table>

The acceptable difference between the measurement result of PTB and KazInMetr follows from:

\[
\Delta_{\text{acceptable}} \leq \sqrt{U_{\text{PTB}}^2 + U_{\text{KazInMetr}}^2}
\]

The acceptable difference is confirmed by the stated uncertainties of the two participants of this bilateral comparison.

7 Results of calibrations
7.1 Results of KazInMetr
Measurements are carried out on the standard machine 8150 TK from Indentec Co. Indenters: standardizing diamond No.03592 for scales HRA, HRC, HRN and hardmetall ball, batch No.52891 for scales HRB, HRT. The following times are set: total force application time 4 s, reading time after application of the preliminary test force 3 s. The range of temperatures for hardness measurements: (18.0-24.0)°C.
The results of the calibrations are contained in Table 2.

### Table 2
Results of calibration of the hardness standard machine of KazInMetr

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Used calibration instrument</th>
<th>Result of calibration (uncertainty of the machine)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preliminary test force, $F_0$</td>
<td>Force transducers 50kgf</td>
<td>0.2 N</td>
</tr>
<tr>
<td>Total test force, $F$</td>
<td>Force transducers 50kgf, 200kgf</td>
<td>1.5 N</td>
</tr>
<tr>
<td>Indentation depth $h$</td>
<td>Gauge blocks</td>
<td>0.2 µm</td>
</tr>
<tr>
<td>Preliminary test force duration time $t_0$</td>
<td>Stop watch</td>
<td>0.1 s</td>
</tr>
<tr>
<td>Indentation velocity</td>
<td>Stop watch</td>
<td>1 µm/s</td>
</tr>
<tr>
<td>Total test force duration time $t$</td>
<td>Stop watch</td>
<td>0.1 s</td>
</tr>
<tr>
<td>Indenter cone angle $\alpha$</td>
<td>Measurement microscope</td>
<td>0.1°</td>
</tr>
<tr>
<td>Indenter radius $r$</td>
<td>Measurement microscope</td>
<td>2 µm</td>
</tr>
<tr>
<td>Diameter of ball indenter</td>
<td>Length measurement machine</td>
<td>2.5 µm</td>
</tr>
<tr>
<td>Deformation of frame</td>
<td>Hardened steel ball</td>
<td>0.3 µm</td>
</tr>
</tbody>
</table>

### 7.2 Results of PTB
Measurements are carried out on the hardness standard machine RNG10 for hardness scales HRA, HRB, HRC and on the hardness standard machine RNG 3 for hardness scales HRN and HRT. The indenters are No.836 for scales HRA, HRC and No 838 for scale HRN and hardmetal ball No. HRB1 for scales HRB, HRT. The following times are set: total force application time 4 s, total force application time: 7 s, reading time after application of the preliminary test force 3 s. The range of temperatures for hardness measurements: (20.0±0.5) °C.

The results of the calibrations are contained in Table 3.

### Table 3
Results of calibration of the hardness standard machine of PTB

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Used calibration instrument</th>
<th>Result of calibration (uncertainty of the machine)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preliminary test force, $F_0$</td>
<td>Force transducer 100 N</td>
<td>0.2 N</td>
</tr>
<tr>
<td>Total test force, $F$</td>
<td>Force transducer 2000 N</td>
<td>1.5 N</td>
</tr>
<tr>
<td>Indentation depth $h$</td>
<td>Laser interferometer</td>
<td>0.05 µm</td>
</tr>
<tr>
<td>Preliminary test force duration time $t_0$</td>
<td>Stop watch</td>
<td>0.1 s</td>
</tr>
<tr>
<td>Indentation velocity</td>
<td>Computer clock</td>
<td>0.5 µm/s</td>
</tr>
<tr>
<td>Total test force duration time $t$</td>
<td>Stop watch</td>
<td>0.1 s</td>
</tr>
</tbody>
</table>
8 Uncertainty budgets
The estimation of the uncertainty follows the guideline EURAMET/cg-16/v.01 [1].

8.1 Sensitivity coefficients of influence quantities
Sensitivity coefficients of influence quantities for the Rockwell hardness scales HRA and HRB are summarized in the Tables 4, 5 and 6.

Table 4: Sensitivity coefficients of influence quantities for Rockwell hardness scale HRA

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
<th>Sensitivity coefficient symbol</th>
<th>Sensitivity coefficient</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preliminary test force</td>
<td>$F_0$</td>
<td>N</td>
<td>$\frac{\Delta HRA}{\Delta F_0}$</td>
<td>-0.00372*Hardness(HRA) + 0.3574</td>
<td>NIST</td>
</tr>
<tr>
<td>Total test force</td>
<td>$F$</td>
<td>N</td>
<td>$\frac{\Delta HRA}{\Delta F}$</td>
<td>0.00137*Hardness(HRA) - 0.1396</td>
<td>NIST</td>
</tr>
<tr>
<td>Permanent depth of indentation</td>
<td>$h$</td>
<td>$\mu$m</td>
<td>$\frac{\Delta HRA}{\Delta h}$</td>
<td>1/2</td>
<td>Definition</td>
</tr>
<tr>
<td>Preliminary test force duration time</td>
<td>$t_0$</td>
<td>s</td>
<td>$\frac{\Delta HRA}{\Delta t_0}$</td>
<td>-0.0011*Hardness(HRA) + 0.0874</td>
<td>NPL</td>
</tr>
<tr>
<td>Indentation velocity</td>
<td>$v$</td>
<td>$\mu$m·s$^{-1}$</td>
<td>$\frac{\Delta HRA}{\Delta v}$</td>
<td>0.00035*Hardness(HRA) - 0.0224</td>
<td>NPL</td>
</tr>
<tr>
<td>Total test force duration time</td>
<td>$t$</td>
<td>s</td>
<td>$\frac{\Delta HRA}{\Delta t}$</td>
<td>0.00160*Hardness(HRA) - 0.162</td>
<td>NPL</td>
</tr>
<tr>
<td>Indenter angle</td>
<td>$a$</td>
<td>°</td>
<td>$\frac{\Delta HRA}{\Delta a}$</td>
<td>0.18</td>
<td>NIM</td>
</tr>
<tr>
<td>Indenter radius</td>
<td>$r$</td>
<td>$\mu$m</td>
<td>$\frac{\Delta HRA}{\Delta r}$</td>
<td>0.058</td>
<td>NIM</td>
</tr>
</tbody>
</table>

Table 5: Sensitivity coefficients of influence quantities for Rockwell hardness scale HRB
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
<th>Sensitivity coefficient symbol</th>
<th>Sensitivity coefficient</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preliminary test force</td>
<td>$F_0$</td>
<td>N</td>
<td>$\frac{\Delta HRB}{\Delta F_0}$</td>
<td>-0.0022*Hardness(HRB) + 0.233</td>
<td>NIST</td>
</tr>
<tr>
<td>Total test force</td>
<td>$F$</td>
<td>N</td>
<td>$\frac{\Delta HRB}{\Delta F}$</td>
<td>0.00092*Hardness(HRB) - 0.139</td>
<td>NIST</td>
</tr>
<tr>
<td>Permanent depth of indentation</td>
<td>$h$</td>
<td>µm</td>
<td>$\frac{\Delta HRB}{\Delta h}$</td>
<td>1 / 2</td>
<td>Definition</td>
</tr>
<tr>
<td>Preliminary test force duration time</td>
<td>$t_0$</td>
<td>s</td>
<td>$\frac{\Delta HRB}{\Delta t_0}$</td>
<td>-0.00009<em>Hardness(HRB)^2 + 0.0128</em>Hardness(HRB) - 0.3254</td>
<td>NPL</td>
</tr>
<tr>
<td>Indentation velocity</td>
<td>$v$</td>
<td>µm·s^{-1}</td>
<td>$\frac{\Delta HRB}{\Delta v}$</td>
<td>-0.00014*Hardness(HRB) + 0.0102</td>
<td>NPL</td>
</tr>
<tr>
<td>Total test force duration time</td>
<td>$t$</td>
<td>s</td>
<td>$\frac{\Delta HRB}{\Delta t}$</td>
<td>-0.017</td>
<td>NIST</td>
</tr>
<tr>
<td>Indenter ball diameter</td>
<td>$d$</td>
<td>µm</td>
<td>$\frac{\Delta HRB}{\Delta d}$</td>
<td>-0.00049*Hardness(HRB) +0.022</td>
<td>NIM</td>
</tr>
</tbody>
</table>

Table 6: Sensitivity coefficients of influence quantities for Rockwell hardness scale HRC

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
<th>Sensitivity coefficients at different hardness levels, HR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>20 to 25</td>
</tr>
<tr>
<td>Preliminary test force</td>
<td>$F_0$</td>
<td>N</td>
<td>1.2*10^{-1}</td>
</tr>
<tr>
<td>Total test force</td>
<td>$F$</td>
<td>N</td>
<td>-4.0*10^{-2}</td>
</tr>
<tr>
<td>Indenter angle</td>
<td>$\alpha$</td>
<td>°</td>
<td>1.3*10^{0}</td>
</tr>
<tr>
<td>Indenter radius</td>
<td>$r$</td>
<td>s</td>
<td>1.5*10^{1}</td>
</tr>
<tr>
<td>Permanent depth of indentation</td>
<td>$h$</td>
<td>µm</td>
<td>-5.0*10^{-1}</td>
</tr>
<tr>
<td>Indentation velocity</td>
<td>$v$</td>
<td>µm·s^{-1}</td>
<td>-2.0*10^{-2}</td>
</tr>
<tr>
<td>Preliminary test force duration time</td>
<td>$t_0$</td>
<td>s</td>
<td>1.0*10^{2}</td>
</tr>
<tr>
<td>Total test force duration time</td>
<td>$t$</td>
<td>s</td>
<td>-7.0*10^{-2}</td>
</tr>
</tbody>
</table>

8.2 Uncertainty budgets of KazInMetr
Based on the sensitivity coefficients in par. 8.1 the following uncertainty budgets for the hardness scales HRA, HRB and HRC can be established for the case of rectangular distribution of the input quantities.

The expanded uncertainty follows from:

$$U_e = 2 \sqrt{ \sum_i (c_i u(x_i))^2 }$$

Table 7A: Example of uncertainty budget for 35 HRA
Uncertainty budget for 35 HRA
<table>
<thead>
<tr>
<th>Quantity $X_i$</th>
<th>Estimated value $\Delta x_i$</th>
<th>Standard uncertainty $u(x_i) = \frac{\Delta x_i}{\sqrt{3}}$</th>
<th>Sensitivity coefficient $C_i$</th>
<th>Uncertainty contribution $u_i(H)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preliminary test force, $F_0$</td>
<td>0.2 N</td>
<td>0.12</td>
<td>0.227</td>
<td>0.026</td>
</tr>
<tr>
<td>Total test force, $F$</td>
<td>1.5 N</td>
<td>0.87</td>
<td>-0.09165</td>
<td>-0.079</td>
</tr>
<tr>
<td>Permanent depth of indentation, $h$</td>
<td>0.2 µm</td>
<td>0.12</td>
<td>0.5</td>
<td>0.058</td>
</tr>
<tr>
<td>Preliminary test force dwell time, $t_0$</td>
<td>1.5 s</td>
<td>0.87</td>
<td>0.0489</td>
<td>0.042</td>
</tr>
<tr>
<td>Indentation velocity, $v$</td>
<td>10 µm·s$^{-1}$</td>
<td>5.77</td>
<td>-0.01015</td>
<td>-0.059</td>
</tr>
<tr>
<td>Total test force dwell time, $t$</td>
<td>2 s</td>
<td>1.15</td>
<td>-0.106</td>
<td>-0.122</td>
</tr>
<tr>
<td>Indenter angle, $\alpha$</td>
<td>0.1°</td>
<td>0.06</td>
<td>0.18</td>
<td>0.010</td>
</tr>
<tr>
<td>Indenter radius, $r$</td>
<td>5 µm</td>
<td>2.89</td>
<td>0.058</td>
<td>0.167</td>
</tr>
<tr>
<td>Deformation of frame, $DF$</td>
<td>0.3 µm</td>
<td>0.17</td>
<td>0.5</td>
<td>0.087</td>
</tr>
<tr>
<td>Combined uncertainty, $u_c$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Expanded uncertainty, $U_e$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 7B: Example of uncertainty budget for 55 HRA

Uncertainty budget for 55 HRA

<table>
<thead>
<tr>
<th>Quantity $X_i$</th>
<th>Estimated value $\Delta x_i$</th>
<th>Standard uncertainty $u(x_i) = \frac{\Delta x_i}{\sqrt{3}}$</th>
<th>Sensitivity coefficient $C_i$</th>
<th>Uncertainty contribution $u_i(H)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preliminary test force, $F_0$</td>
<td>0.2 N</td>
<td>0.12</td>
<td>0.153</td>
<td>0.018</td>
</tr>
<tr>
<td>Total test force, $F$</td>
<td>1.5 N</td>
<td>0.87</td>
<td>-0.06425</td>
<td>-0.056</td>
</tr>
<tr>
<td>Permanent depth of indentation, $h$</td>
<td>0.2 µm</td>
<td>0.12</td>
<td>0.5</td>
<td>0.058</td>
</tr>
<tr>
<td>Preliminary test force dwell time, $t_0$</td>
<td>1.5 s</td>
<td>0.87</td>
<td>0.0269</td>
<td>0.023</td>
</tr>
<tr>
<td>Indentation velocity, $v$</td>
<td>10 µm·s$^{-1}$</td>
<td>5.77</td>
<td>-0.00315</td>
<td>-0.018</td>
</tr>
<tr>
<td>Total test force dwell time, $t$</td>
<td>2 s</td>
<td>1.15</td>
<td>-0.074</td>
<td>-0.085</td>
</tr>
<tr>
<td>Indenter angle, $\alpha$</td>
<td>0.1°</td>
<td>0.06</td>
<td>0.18</td>
<td>0.010</td>
</tr>
<tr>
<td>Indenter radius, $r$</td>
<td>5 µm</td>
<td>2.89</td>
<td>0.058</td>
<td>0.167</td>
</tr>
<tr>
<td>Deformation of frame, $DF$</td>
<td>0.3 µm</td>
<td>0.17</td>
<td>0.5</td>
<td>0.087</td>
</tr>
<tr>
<td>Combined uncertainty, $u_c$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Expanded uncertainty, $U_e$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 7C: Example of uncertainty budget for 85 HRA

Uncertainty budget for 85 HRA

<table>
<thead>
<tr>
<th>Quantity $X_i$</th>
<th>Estimated value $\Delta x_i$</th>
<th>Standard uncertainty $u(x_i) = \frac{\Delta x_i}{\sqrt{3}}$</th>
<th>Sensitivity coefficient $C_i$</th>
<th>Uncertainty contribution $u_i(H)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preliminary test force, $F_0$</td>
<td>0.2 N</td>
<td>0.12</td>
<td>0.153</td>
<td>0.018</td>
</tr>
<tr>
<td>Total test force, $F$</td>
<td>1.5 N</td>
<td>0.87</td>
<td>-0.06425</td>
<td>-0.056</td>
</tr>
<tr>
<td>Permanent depth of indentation, $h$</td>
<td>0.2 µm</td>
<td>0.12</td>
<td>0.5</td>
<td>0.058</td>
</tr>
<tr>
<td>Preliminary test force dwell time, $t_0$</td>
<td>1.5 s</td>
<td>0.87</td>
<td>0.0269</td>
<td>0.023</td>
</tr>
<tr>
<td>Indentation velocity, $v$</td>
<td>10 µm·s$^{-1}$</td>
<td>5.77</td>
<td>-0.00315</td>
<td>-0.018</td>
</tr>
<tr>
<td>Total test force dwell time, $t$</td>
<td>2 s</td>
<td>1.15</td>
<td>-0.074</td>
<td>-0.085</td>
</tr>
<tr>
<td>Indenter angle, $\alpha$</td>
<td>0.1°</td>
<td>0.06</td>
<td>0.18</td>
<td>0.010</td>
</tr>
<tr>
<td>Indenter radius, $r$</td>
<td>5 µm</td>
<td>2.89</td>
<td>0.058</td>
<td>0.167</td>
</tr>
<tr>
<td>Deformation of frame, $DF$</td>
<td>0.3 µm</td>
<td>0.17</td>
<td>0.5</td>
<td>0.087</td>
</tr>
<tr>
<td>Combined uncertainty, $u_c$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Expanded uncertainty, $U_e$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 7C: Example of uncertainty budget for 85 HRA

Uncertainty budget for 85 HRA

<table>
<thead>
<tr>
<th>Quantity $X_i$</th>
<th>Estimated value $\Delta x_i$</th>
<th>Standard uncertainty $u(x_i) = \frac{\Delta x_i}{\sqrt{3}}$</th>
<th>Sensitivity coefficient $C_i$</th>
<th>Uncertainty contribution $u_i(H)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preliminary test force, $F_0$</td>
<td>0.2 N</td>
<td>0.12</td>
<td>0.153</td>
<td>0.018</td>
</tr>
<tr>
<td>Total test force, $F$</td>
<td>1.5 N</td>
<td>0.87</td>
<td>-0.06425</td>
<td>-0.056</td>
</tr>
<tr>
<td>Permanent depth of indentation, $h$</td>
<td>0.2 µm</td>
<td>0.12</td>
<td>0.5</td>
<td>0.058</td>
</tr>
<tr>
<td>Preliminary test force dwell time, $t_0$</td>
<td>1.5 s</td>
<td>0.87</td>
<td>0.0269</td>
<td>0.023</td>
</tr>
<tr>
<td>Indentation velocity, $v$</td>
<td>10 µm·s$^{-1}$</td>
<td>5.77</td>
<td>-0.00315</td>
<td>-0.018</td>
</tr>
<tr>
<td>Total test force dwell time, $t$</td>
<td>2 s</td>
<td>1.15</td>
<td>-0.074</td>
<td>-0.085</td>
</tr>
<tr>
<td>Indenter angle, $\alpha$</td>
<td>0.1°</td>
<td>0.06</td>
<td>0.18</td>
<td>0.010</td>
</tr>
<tr>
<td>Indenter radius, $r$</td>
<td>5 µm</td>
<td>2.89</td>
<td>0.058</td>
<td>0.167</td>
</tr>
<tr>
<td>Deformation of frame, $DF$</td>
<td>0.3 µm</td>
<td>0.17</td>
<td>0.5</td>
<td>0.087</td>
</tr>
<tr>
<td>Combined uncertainty, $u_c$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Expanded uncertainty, $U_e$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 7C: Example of uncertainty budget for 85 HRA

Uncertainty budget for 85 HRA
<table>
<thead>
<tr>
<th>Quantity $X_i$</th>
<th>Estimated value $\Delta x_i$</th>
<th>Standard uncertainty $u(x_i) = \frac{\Delta x_i}{\sqrt{3}}$</th>
<th>Sensitivity coefficient $C_i$</th>
<th>Uncertainty contribution $u_i(H)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preliminary test force, $F_0$</td>
<td>0.2 N</td>
<td>0.12</td>
<td>0.041</td>
<td>0.005</td>
</tr>
<tr>
<td>Total test force, $F$</td>
<td>1.5 N</td>
<td>0.87</td>
<td>-0.02315</td>
<td>-0.020</td>
</tr>
<tr>
<td>Permanent depth of indentation, $h$</td>
<td>0.2 µm</td>
<td>0.12</td>
<td>0.5</td>
<td>0.058</td>
</tr>
<tr>
<td>Preliminary test force duration, $t_0$</td>
<td>1.5 s</td>
<td>0.87</td>
<td>-0.0061</td>
<td>-0.005</td>
</tr>
<tr>
<td>Indentation velocity, $v$</td>
<td>10 µm·s⁻¹</td>
<td>5.77</td>
<td>0.00735</td>
<td>0.042</td>
</tr>
<tr>
<td>Total test force duration time, $t$</td>
<td>2 s</td>
<td>1.15</td>
<td>-0.026</td>
<td>-0.030</td>
</tr>
<tr>
<td>Indenter angle, $\alpha$</td>
<td>0.1 °</td>
<td>0.06</td>
<td>0.18</td>
<td>0.010</td>
</tr>
<tr>
<td>Indenter radius, $r$</td>
<td>5 µm</td>
<td>2.89</td>
<td>0.058</td>
<td>0.167</td>
</tr>
<tr>
<td>Deformation of frame, $DF$</td>
<td>0.3 µm</td>
<td>0.17</td>
<td>0.5</td>
<td>0.087</td>
</tr>
<tr>
<td>Combined uncertainty, $u_c$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Expanded uncertainty, $U_e$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 7D: Example of uncertainty budget for 25 HRB

Uncertainty budget for 25 HRB

<table>
<thead>
<tr>
<th>Quantity $X_i$</th>
<th>Estimated value $\Delta x_i$</th>
<th>Standard uncertainty $u(x_i) = \frac{\Delta x_i}{\sqrt{3}}$</th>
<th>Sensitivity coefficient $C_i$</th>
<th>Uncertainty contribution $u_i(H)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preliminary test force, $F_0$</td>
<td>0.2 N</td>
<td>0.12</td>
<td>0.178</td>
<td>0.021</td>
</tr>
<tr>
<td>Total test force, $F$</td>
<td>1.5 N</td>
<td>0.87</td>
<td>-0.116</td>
<td>-0.100</td>
</tr>
<tr>
<td>Permanent depth of indentation, $h$</td>
<td>0.2 µm</td>
<td>0.12</td>
<td>0.5</td>
<td>0.058</td>
</tr>
<tr>
<td>Preliminary test force dwell time, $t_0$</td>
<td>1.5 s</td>
<td>0.87</td>
<td>-0.06165</td>
<td>-0.053</td>
</tr>
<tr>
<td>Indentation velocity, $v$</td>
<td>10 µm·s⁻¹</td>
<td>5.77</td>
<td>0.0137</td>
<td>0.079</td>
</tr>
<tr>
<td>Total test force duration time, $t$</td>
<td>2 s</td>
<td>1.15</td>
<td>-0.017</td>
<td>-0.020</td>
</tr>
<tr>
<td>Indenter ball diameter, $d$</td>
<td>1 µm</td>
<td>0.58</td>
<td>0.00975</td>
<td>0.006</td>
</tr>
<tr>
<td>Deformation of frame, $DF$</td>
<td>0.3 µm</td>
<td>0.17</td>
<td>0.5</td>
<td>0.087</td>
</tr>
<tr>
<td>Combined uncertainty, $u_c$</td>
<td></td>
<td></td>
<td>k=2</td>
<td>0.176</td>
</tr>
<tr>
<td>Expanded uncertainty, $U_e$</td>
<td></td>
<td></td>
<td></td>
<td>0.35</td>
</tr>
</tbody>
</table>

Table 7E: Example of uncertainty budget for 60 HRB

Uncertainty budget for 60 HRB

8
Table 7F: Example of uncertainty budget for 100 HRB

<table>
<thead>
<tr>
<th>Quantity X_i</th>
<th>Estimated value Δx_i</th>
<th>Standard uncertainty $u(x_i) = \frac{\Delta x_i}{\sqrt{3}}$</th>
<th>Sensitivity coefficient C_i</th>
<th>Uncertainty contribution $u_i(H)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preliminary test force, $F_0$</td>
<td>0.2 N</td>
<td>0.12</td>
<td>0.101</td>
<td>0.012</td>
</tr>
<tr>
<td>Total test force, $F$</td>
<td>1.5 N</td>
<td>0.87</td>
<td>-0.0838</td>
<td>-0.073</td>
</tr>
<tr>
<td>Permanent depth of indentation, $h$</td>
<td>0.2 µm</td>
<td>0.12</td>
<td>0.5</td>
<td>0.058</td>
</tr>
<tr>
<td>Preliminary test force duration time, $t_0$</td>
<td>1.5 s</td>
<td>0.87</td>
<td>0.1186</td>
<td>0.103</td>
</tr>
<tr>
<td>Indentation velocity, $v$</td>
<td>10 µm·s$^{-1}$</td>
<td>5.77</td>
<td>0.0186</td>
<td>0.107</td>
</tr>
<tr>
<td>Total test force dwell time, $t$</td>
<td>2 s</td>
<td>1.15</td>
<td>-0.017</td>
<td>-0.020</td>
</tr>
<tr>
<td>Indenter ball diameter, $d$</td>
<td>1 µm</td>
<td>0.06</td>
<td>-0.0074</td>
<td>0.004</td>
</tr>
<tr>
<td>Deformation of frame, $DF$</td>
<td>0.3 µm</td>
<td>0.17</td>
<td>0.5</td>
<td>0.087</td>
</tr>
<tr>
<td>Combined uncertainty, $u_c$</td>
<td></td>
<td></td>
<td></td>
<td>k=2</td>
</tr>
<tr>
<td>Expanded uncertainty, $U_e$</td>
<td></td>
<td></td>
<td></td>
<td>0.197</td>
</tr>
</tbody>
</table>

Table 7G: Example of uncertainty budget for HRC

Uncertainty budget for 3 levels HRC

<table>
<thead>
<tr>
<th>Quantity X_i</th>
<th>Estimated value Δx_i</th>
<th>Standard uncertainty $u(x_i) = \frac{\Delta x_i}{\sqrt{3}}$</th>
<th>Sensitivity coefficient C_i</th>
<th>Uncertainty contribution $u_i(H)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preliminary test force, $F_0$</td>
<td>0.2 N</td>
<td>0.12</td>
<td>0.013</td>
<td>0.002</td>
</tr>
<tr>
<td>Total test force, $F$</td>
<td>1.5 N</td>
<td>0.87</td>
<td>-0.047</td>
<td>-0.041</td>
</tr>
<tr>
<td>Permanent depth of indentation, $h$</td>
<td>0.2 µm</td>
<td>0.12</td>
<td>0.5</td>
<td>0.058</td>
</tr>
<tr>
<td>Preliminary test force dwell time, $t_0$</td>
<td>1.5 s</td>
<td>0.87</td>
<td>0.0546</td>
<td>0.047</td>
</tr>
<tr>
<td>Indentation velocity, $v$</td>
<td>10 µm·s$^{-1}$</td>
<td>5.77</td>
<td>-0.0242</td>
<td>0.140</td>
</tr>
<tr>
<td>Total test force dwell time, $t$</td>
<td>2 s</td>
<td>1.15</td>
<td>-0.017</td>
<td>-0.020</td>
</tr>
<tr>
<td>Indenter ball diameter, $d$</td>
<td>1 µm</td>
<td>0.58</td>
<td>-0.027</td>
<td>-0.016</td>
</tr>
<tr>
<td>Deformation of frame, $DF$</td>
<td>0.3 µm</td>
<td>0.17</td>
<td>0.5</td>
<td>0.087</td>
</tr>
<tr>
<td>Combined uncertainty, $u_c$</td>
<td></td>
<td></td>
<td></td>
<td>k=2</td>
</tr>
<tr>
<td>Expanded uncertainty, $U_e$</td>
<td></td>
<td></td>
<td></td>
<td>0.187</td>
</tr>
</tbody>
</table>
9 Degree of equivalence

The degree of equivalence according to [2] is calculated as the pair of values \((d_{i,j}, U(d_{i,j}))\) using

\[ d_{i,j} = x_i - x_j \]

\[ U(d_{i,j}) = 2u(d_{i,j}) \]

where \(u(d_{i,j})\) is given by

\[ u^2(d_{i,j}) = u^2(x_i) + u^2(x_j) \]

The degrees of equivalence are listed in Table 8.

Table 8
Degrees of equivalence of the comparison

<table>
<thead>
<tr>
<th>Hardness scale</th>
<th>(x_i)</th>
<th>(x_j)</th>
<th>(u(x_i))</th>
<th>(u(x_j))</th>
<th>(d_{i,j})</th>
<th>(U(d_{i,j}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>60 HRA</td>
<td>59.84</td>
<td>59.90</td>
<td>0.15</td>
<td>0.25</td>
<td>-0.06</td>
<td>0.58</td>
</tr>
<tr>
<td>70 HRA</td>
<td>71.33</td>
<td>71.10</td>
<td>0.15</td>
<td>0.25</td>
<td>+0.23</td>
<td>0.58</td>
</tr>
<tr>
<td>80 HRA</td>
<td>81.36</td>
<td>81.26</td>
<td>0.15</td>
<td>0.25</td>
<td>+0.10</td>
<td>0.58</td>
</tr>
<tr>
<td>60 HRB</td>
<td>59.03</td>
<td>58.36</td>
<td>0.25</td>
<td>0.40</td>
<td>+0.67</td>
<td>0.94</td>
</tr>
<tr>
<td>75 HRB</td>
<td>75.76</td>
<td>75.08</td>
<td>0.25</td>
<td>0.40</td>
<td>+0.68</td>
<td>0.94</td>
</tr>
<tr>
<td>100 HRB</td>
<td>97.64</td>
<td>97.04</td>
<td>0.25</td>
<td>0.40</td>
<td>+0.60</td>
<td>0.94</td>
</tr>
<tr>
<td>30 HRC</td>
<td>29.34</td>
<td>29.36</td>
<td>0.15</td>
<td>0.25</td>
<td>-0.02</td>
<td>0.58</td>
</tr>
<tr>
<td>50 HRC</td>
<td>49.84</td>
<td>49.71</td>
<td>0.15</td>
<td>0.25</td>
<td>+0.13</td>
<td>0.58</td>
</tr>
<tr>
<td>65 HRC</td>
<td>62.79</td>
<td>62.76</td>
<td>0.15</td>
<td>0.25</td>
<td>+0.03</td>
<td>0.58</td>
</tr>
<tr>
<td>70HR15N</td>
<td>71.00</td>
<td>70.85</td>
<td>0.20</td>
<td>0.35</td>
<td>+0.15</td>
<td>0.81</td>
</tr>
<tr>
<td>80HR15N</td>
<td>81.73</td>
<td>81.35</td>
<td>0.20</td>
<td>0.35</td>
<td>+0.38</td>
<td>0.81</td>
</tr>
<tr>
<td>90HR15N</td>
<td>89.87</td>
<td>89.83</td>
<td>0.20</td>
<td>0.35</td>
<td>+0.04</td>
<td>0.81</td>
</tr>
<tr>
<td>50HR30N</td>
<td>49.44</td>
<td>49.46</td>
<td>0.20</td>
<td>0.35</td>
<td>-0.02</td>
<td>0.81</td>
</tr>
</tbody>
</table>
### 10 Discussions, conclusions and remarks

The COOMET Rockwell PTB/KazInMetr comparison can be considered as a successful metrological exercise. The stated uncertainties were confirmed by the found measurement result differences. It is recommended to concentrate metrological investigations on the influence of ball indenter deviations at the HRT scale.

### 11 Reference


### Appendix

**A1 Description of the instruments by the participants**

**A1.1 Hardness standard machines of PTB**

1) **Hardness standard machine RNG 10**

The hardness standard machine RNG10 manufactured by PGH Kraftmessgeräte Halle (Germany) is intended for the Rockwell hardness scales HRA, HRB and HRC. It contains two suspensions, where the upper suspension with a mass of 10 kg generates the preliminary test force of 98.07 N and the lower suspension takes the corresponding deadweights which generate the additional test force. The measurement of the indentation depth is realized with a laser interferometer from SIOS Co. in Ilmenau with a resolution of 2 nm. The vertical movement of the indenter together with the suspensions is carried out with an electrical motor driving a ball screw spindle. As diamond Rockwell indenters one of a group standard consisting of four indenters is used. The Force-time-pattern according to ISO 6508 is realized with a control computer by Siemens Co. and a personal computer.

2) **Hardness standard machine RNG 3**

The hardness standard machine RNG3 manufactured by PGH Kraftmessgeräte Halle (Germany) is intended for the Superficial Rockwell hardness scales HRN and HRT. It contains two suspensions, where the upper suspension with a mass of 3 kg generates the preliminary test force of 29.42 N and the lower suspension takes the corresponding deadweights which generate the additional test force.
The vertical movement of the indenters together with the suspensions is carried out by a hydraulic piston driven by an oil pump with nozzles for the control of the force application velocity. The measurement of the indentation depth is realized with a laser interferometer from SIOS Co. in Ilmenau with a resolution of 2 nm. As diamond Rockwell indenters one of a group standard consisting of four indenters is used. The Force-time-pattern according to ISO 6508 is realized with an electro-hydraulic control system together with a software control on a personal computer.

**A1.2 Hardness standard machine of KazInMetr**


This machine is intended for the calibration of Rockwell hardness test blocks, and is designed to meet the requirements of ISO 6508.

It is fitted with a motorized leadscrew, which is used to raise the test block into the correct position. A test block is supported on a special tungsten carbide anvil. The machine has a lever system with automatic cycle applied forces. The resolution of the measuring device is 0,01 HR. The measuring device of standard machine has a linear transducer.