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DESIGN AND CAPABILITY OF A NEW CALIBRATION MACHINE FOR THE MACRO RANGE OF INSTRUMENTED INDENTATION TEST

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Abstract: The instrumented indentation test provides a versatile method to determine several materials parameter. In order to provide reference specimens, a calibration machine according to ISO 14577-3 is designed for the macro range. Using innovative technology, the new machine design may lead to a standard solution not only for calibration machines.

Keywords: indentation, reference, uncertainty, machine design.

1. INTRODUCTION

Several materials parameter can be determined by the instrumented indentation test according to ISO 14577 [1]. Calibrated reference specimens for the materials parameters must be available not only in the nano and micro range [2] but also in the macro range. Therefore, a calibration machine of certain type is needed to fulfil the requirements given in the parts 2 and 3 of the standard. The paper presents a new calibration machine for the macro range with the aim to calibrate reference specimens and to validate new test methods. The design allows to use the machine in the macro range but also in the upper micro range.

2. MACHINE DESIGN

2.1. Objectives

The machine should be used up to 1000 N with the ability in mind to reach the upper micro range according to the definition in ISO 14577. Force measurement down to 1 N should be done with a measurement uncertainty of 5 mN. A range of displacement up to several millimetres is necessary to accommodate different types and sizes of specimen and should be measured with uncertainties of 9 nm for indentation depth up to 220 µm. However, the capability for calibration of reference specimens is limited by the uncertainty in compliance of the machine [3]. The aim is to achieve an uncertainty in determining the compliance of 0.5 nm/N on those parts which have a direct impact on the displacement measurement. The machine should accommodate triangular, quadrangular as well as round specimens with sizes up to 70 mm x 70 mm x 17 mm in an interchangeable tray. The specimen should be fixed in place to avoid a lateral movement during the indentation process, but has to be moved to change the indentation position or travel to the integrated microscope for optical inspection. The indenter must be replaceable and separated from the force transducer, but located in a way that allows only axial movements.

Indenter, force transducer, displacement-measuring system, and displacement-generating elements should be guided in such a way, that only linear movements in the axis of the force application are possible to fulfil Abbe's law. To achieve minor measurement uncertainties, the ability to calibrate force and displacement with built in sensors, as given by ISO 14577, should be a prominent design characteristic.

2.2. Design characteristics

Successful realisation of such demanding specifications requires an all-embracing design approach to abandon trodden paths. The approach is based on 5 fundamental design characteristics which will be presented in this paper.

2.2.1 Inverse layout

The solution to most of the mentioned design restrictions is the inverted arrangement of the indenter, force transducer and mechanical elements which provide the necessary force and displacement. Figure 1 shows the principal layout of the machine with the specimen adjacent to the thrust bearing on top of the separated indenter-support. Force transducer and indenter-support are axial restraint by a leaf spring system which guides the movement created by the piezotranslator and satellite roller screw system.

Achieving a small compliance of the machine is a challenging goal, a solution would be to carve the machine out of a solid block of steel. This rather impractical approach eliminates all the joints and contact surfaces between different parts which create most of the undesired compliance. The inverse layout gives the chance to establish stable conditions by using gravity to preload the parts and joints in such a way, that load alternation or a zero force load state is eliminated. All parts, including the outer frame and sensor chain, are preloaded by gravity in the same direction as the direction of the additional load during the measurement process.

The displacement generating system is situated at the bottom of the main load frame and consists of two independent parts. The Physik Instrumente (PI) GmbH & Co. KG P-246K020 piezotranslator allows small movements up to 300 µm with nm-resolution and is intended for testing very hard materials with high testing forces where smooth movements are vital for closed-loop control of the translator.

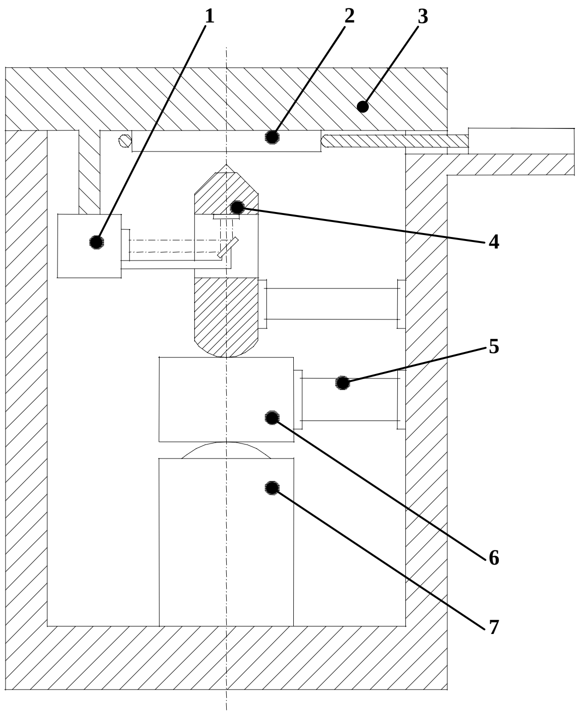

Fig. 1. Schematic layout of main systems: 1 laser interferometer with support bar for tilted mirror, 2 specimen, 3 thrust bearing, 4 indenter with support frame and reflective mirror, 5 leaf spring axial bearing, 6 force transducer, 7 piezotranslator / satellite roller screw.

Because of the possibility to change the displacement rapidly, the piezotranslator may prove its worth in dynamic hardness testing. The detection of the contact between the indenter tip and the specimen surface should be an easy task if it is performed using the piezotranslator which generates vibration on the indenter. The damping of the vibration by touching the surface is detected by the displacement sensor.

The second part of the displacement generating system produces very large displacements up to several millimetres, albeit with much lower resolution. A high precision satellite roller screw by Rollvis S.A. in concert with a high resolution backlash-free servo drive by Harmonic Drive AG is responsible for generating the high displacement rates needed for indenting soft materials. Because of the fixed position of the thrust bearing, the position of the indenter tip is connected to the individual specimen thickness and varies by 12 mm; only the satellite roller screw is able to travel the indenter the required ways and places the piezotranslator with the indenter in the proximity of the specimen.

In our experience there is an undesired influence due to tilting motion of the indenter during indentation process. Such motion is normally permitted by the force transducer which acts as a linear bearing for the flanged indenter. To avoid that influence, the force transducer is separated from the indenter and separately guided by a leaf spring system which allows only axial movements. A second leaf spring system guides the force transducer which is not rigidly flanged to the piezotranslator. Force transducers can therefore be exchanged without time consuming adjustments.

2.2.2 Feed motion guided by leaf springs

Precise axial guidance of indenter-support and force transducer is vital to achieve low measurement uncertainties. The difficulties to create true linear motion which is stick-slip free and almost frictionless are very high. Care must be taken in selecting the appropriate bearing; a number of different types can be found on present machines:

- ball bearing / sleeve bearing; not suitable because of stick-slip and high friction when backlash-free,
- hydrostatic and hydrodynamic liquid bearing; not suitable because of high friction in hydraulic seal,
- hydrostatic and hydrodynamic air cushion bearing; not suitable due to leakage air rate which disturbs the measurement of the laser interferometer.

A leaf spring linear bearing according to Figure 2 was selected as the best compromise in achieving the desired precision.

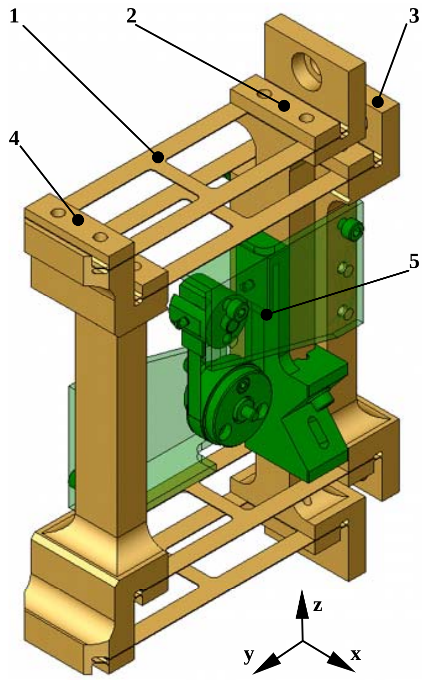

Fig. 2. Leaf spring linear bearing module: 1 leaf spring, 2 inner support bar, 3 outer support bar, 4 common support bar, x lateral load, y longitudinal load, z direction of linear movement. Apparatus 5 (green) forces the common support bar 4 to travel half the way of the total linear movement between 2 and 3.

The linear bearing module consists of two sets of flat leaf springs. Each set of two leaf springs is attached to a support bar via a slot which is bended by screws to clamp the spring. A true linear motion between the inner and outer support bar is created if the common support bar travels half the way of the total linear movement. Such layout shows a certain amount of resistance against longitudinal loads, dependent on the geometrical proportion – especially the thickness – of the leaf spring. The resistance against a lateral load is much higher but bears a significant disadvantage in it; lateral forces can create twisting and buckling of the springs. Rectangular cut-outs and a cross brace in the middle of the leaf spring reduce the tendency to buckle. For the use in the calibration machine, four leaf spring linear bearing modules are arranged in cruciform to benefit from the resistance against lateral loads (Fig. 3).

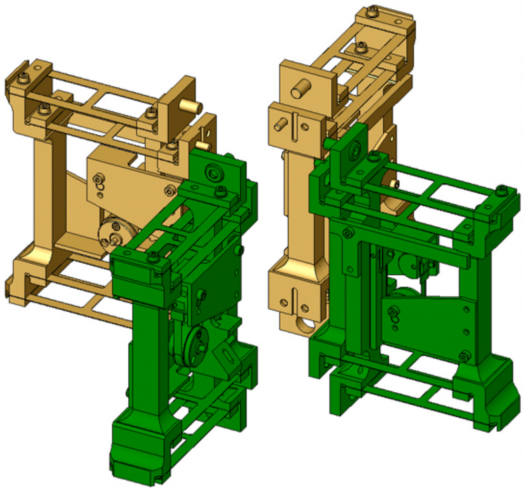

Fig. 3. Leaf spring axial bearing, arranged with four bearing modules in cruciform.

All leaf spring axial bearings have a displacement of about 400 µm at maximum due to the combined displacement of the piezotranslator and the deformation of the force transducer. Leaf springs create stick-slip free nearly frictionless movement without backlash. Proper manufactured and adjusted leaf spring axial bearings show negligible effects on the force measurement in the calibration machine. Manufacturing such a system out of a solid block is the technically correct solution but tend to be a very expensive and difficult task. Constructed of many component parts, the system is difficult to adjust and not free of undesired loads on the force measurement due to tolerances in manufacturing, but able to produce a smooth true linear movement for the indenter and force transducer with sufficient resistance against side forces.

2.2.3. Mass balancing of the indenter

Mass balancing of the indenter and support frame is necessary because of the additional weight on the force transducer due to the inverted layout (Fig. 1). The displacement measuring system consists of two fixed laser interferometers which are mounted perpendicular to the moving direction of the indenter. In order to fulfil Abbe´s rule the reflective mirror must be mounted within the indenter axis which demands a support bar for a tilted mirror between force transducer and indenter (Fig. 1 and 4). The support frame for the indenter and the support bar for the reflective mirror are separated from the force transducer to avoid lateral forces during the penetration of the indenter into the specimen. An opening in the support frame allows movement while guiding the displacement to the indenter.

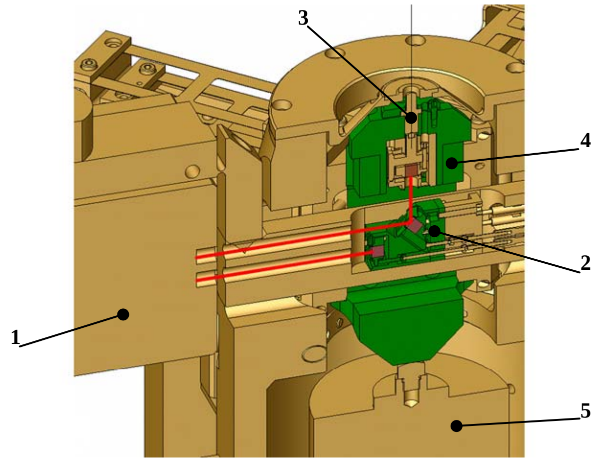

Fig. 4. Arrangement of the fixed laser interferometer (1) and tilted mirror (2). Indenter (3) and support frame (4, green) on top of the force transducer (5).

Because of the inverted layout, the heavy support frame creates an undesired initial compression on the force transducer before contacting the specimen. Therefore the force transducer would not be used within the optimal range of the force measurement. For the purpose of balancing the additional mass, two immersed bodies provide sufficient buoyancy to create a small, adjustable compression on the force transducer, following the main design principle of avoiding zero crossings (Fig 5).

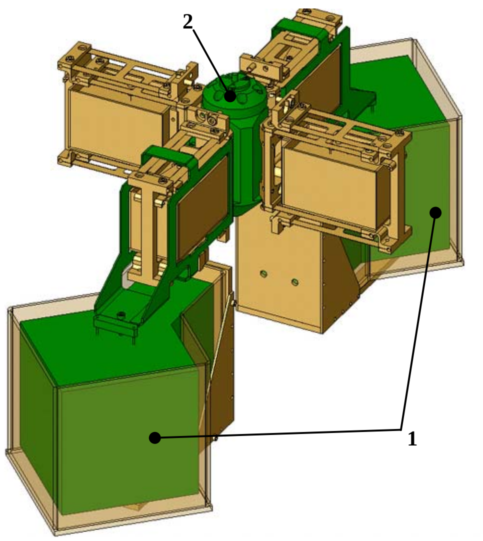

Fig. 5. Arrangement of the mass balancing system: Immersed bodies (1) provide buoyancy to the indenter support frame (2).

The amount of buoyancy created by the immersed bodies is not affected by temperature changes of the liquid and does not have an impact on the force measurement if the two immersed bodies show nearly equal buoyancy. Mass balancing allows the use of changeable force transducers with different force ranges. In that way, calibration of reference materials is also possible in the upper micro range down to 0.5 N.

2.2.4. Fixed thrust bearing, movable specimen

A fixed thrust bearing for the specimen is placed on top of the machine and consist of a massive stone-plate made of Diabas. The laser interferometer for displacement measurement between indenter and specimen is mounted on the plate and measures the back end of the indenter. Therefore, the compliance which affected measurement is determined by the rigidity of the stone-plate and the compliances of indenter and specimen. Compliances of every other part of the machine do not enter into displacement measurement.

The specimen lies closed to the plate if friction-locked clamped during measurement, but lift off the plate with the help of gravity if released for moving to other coordinates or to the microscope. The clamping takes place with the help of the satellite roller screw, which lifts the whole indenter, force transducer and piezotranslator unit in the proximity of the specimen to compensate for different specimen-widths and press the specimen with a spring against the stone-plate simultaneously (Fig. 6).

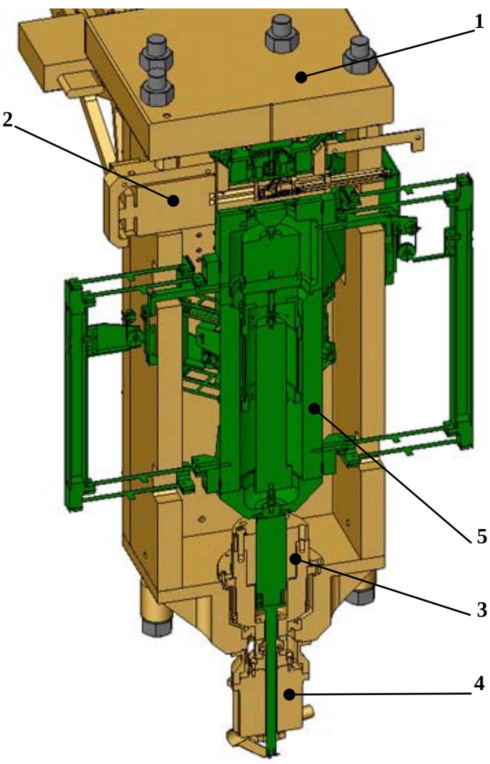

Fig. 6. Fixed thrust bearing (1) with mounted laser interferometer (2). The satellite roller screw (3) with attached servo drive (4) lifts off the indenter / load-cell / piezotranslator unit (5, green) to press the specimen against the thrust bearing.

Three high precision translation stages by Physik Instrumente (PI) GmbH & Co. KG are in a way arranged to allow free two-dimensional movements of the specimen around the indenter and microscope positions.

Using an overview image of the actual specimen displayed on the PC screen should be used by the operator to determine the position of the indentation by a mouse click. With the help of the computer controlled translation stages, automatic transaction of series of tests without intervention of the operator are possible. An integrated microscope permits a detailed look at the indentation. All images and positions as well as the data of the indentation experiments are stored in a database for future reference. Further experiments could be easily undertaken due to an appropriate identification system, a precise specimen clamping / positioning and the knowledge of earlier indentation-positions through the database.

2.2.5 Bore in thrust bearing

A drill hole through the stone-plate in the axis of the indenter gives plenty of opportunities for reducing the uncertainty of force and displacement measurement. The most important feature can be found in determining changes of the specimens back position. Unlike other instrumented indentation test machines, the displacement of the indenter against the specimen is measured directly over the contact area between the back of the specimen and the thrust bearing. Therefore, bending and changes in the contact area of the specimen falsify the displacement measurement. A second laser interferometer on top of the thrust bearing in combination with a tracer pin is able to measure possible movements of the back of the specimen through the drill hole.

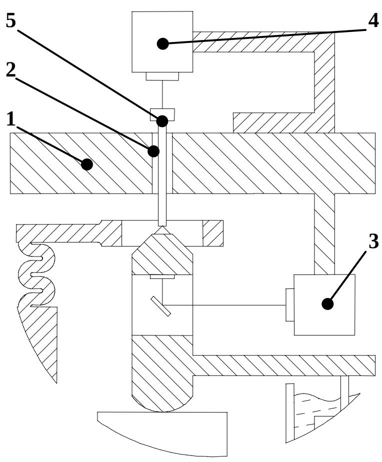

Fig. 7. Arrangement for displacement calibration. A comparison of measured values of the primary (3) and second laser interferometer (4) in combination with a tracer pin (5) is possible by using the drill hole (2) in the thrust bearing (1).

As mentioned above, the ability to calibrate force and displacement with built in sensors, as given by ISO 14577, should be feasible. A comparison of the measured values between both interferometer with the use of the tracer pin as a connection and the satellite roller screw / piezotranslator for moving the reflector mirrors appears meaningful (Fig.7). Placing calibration weights on the tracer pin permits calibration or plausibility checks of the built in force transducer (Fig. 8).

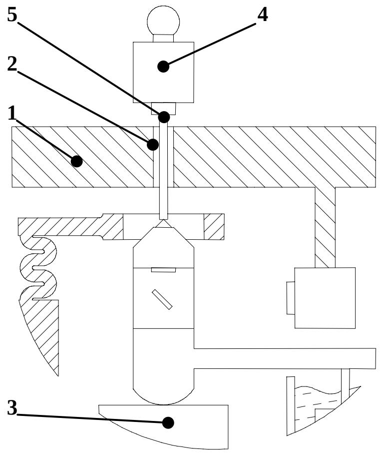

Fig. 8. Arrangement for force calibration. A calibration of the force transducer (3) with a calibration weight (4) in connection with a tracer pin (5) by using the drill hole (2) in the thrust bearing (1).

3. CONCLUSION

Most of the vital mechanical functions are tested successfully and adjustments are made. The required software and electronics for controlling the machine and performing automatic series of measurements are currently under development and manufacturing at BAM.

REFERENCES

[1] ISO 14577: Metallic materials - Instrumented indentation test for hardness and other materials parameters; October 2003
- part 1: Test method
- part 2: Verification and calibration of the testing machine
- part 3: Calibration of reference test pieces.

[2] K. Herrmann, N.M. Jennett, S. Kuypers, I. McEntegaart, C. Ingelbrecht, U. Hangen, T. Chudoba, F. Pohlenz, F. Menelao, ”Investigation of the poroperties of candidate reference materials suited for the calibration of nanoindentation instruments“, *Zeitschrift Metallkunde*, vol. 95, pp. 802-806.

[3] Ch. Ullner, “Critical points in ISO 14577 part 2 and 3 considering the uncertainty in measurement,” Proc. of HARDMEKO 2004, 11-12 November, 2004, Washington D.C., USA