A New Consideration in the Measurement Uncertainty of Indicators

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Abstract: *The internal mechanism of conventional contact-gauging instruments, namely mechanical dial and electronic indicators, is a potential source of errors. Tests performed on some high-accuracy indicators revealed systematic effects of spring rate and substantial force variations in both directions. Stick-slip friction forces of bearing and wiper caused additional variations. Analyses of contact confirmed that these force uncertainties can generate contact uncertainties well above the level of concern on common conditions of engineering surfaces. A new consideration in the analyses of the measurement error budget of these instruments is introduced here. The potential errors induced by the complex behaviour of contact between measuring probe tips and engineering surfaces are of concern in this study. These potential errors are usually neglected by researchers.*

Keywords: *Indicators, measurement error, measurement uncertainty, contact gauging*

1. Introduction

History gives us every reason to expect greater demands for precision during the next decade. Since the 1940s, typical machining tolerances have become about 50% tighter every ten years, continually shifting the accepted meaning of "high precision" – from 0.05 mm in the 1940s to 0.02 mm in 1950s, all the way to 1 μm by 2000. This is evident from Taniguchi's survey of the historical development of the achievable accuracy of material processing over the past century shown in Figure 1 [1]. Depending on his extrapolations, normal machining processes will be capable of producing components of tolerances down to 0.1 μm by about 2030. Accordingly, a development in precision inspection tools conventionally used in precision machine-shops and quality control checkpoints (e.g., co-ordinate measuring machines and indicators) is confidently expected in order to fulfil such increasing requirements. There is a widely-used guideline that the process capability at each step of a traceability (calibration) chain should be ten times better than the previous step. Although, in practice, technological and economic constraints often lead to agreement to use a lower

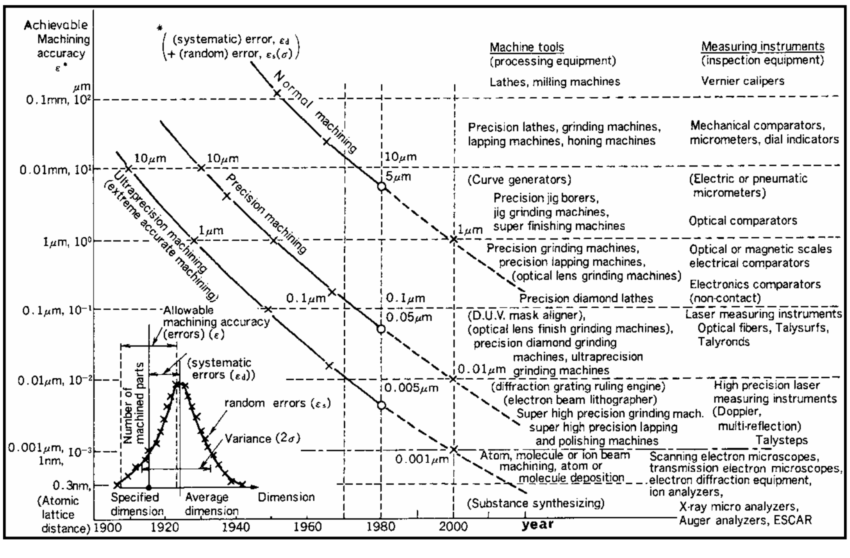

Figure 1
Taniguchi's plot of the historical progress of achievable machining accuracy over the past century [1].

figure, there may be demands for uncertainties of around 100 nm, or smaller, from such instruments within the next twenty years. Well before that, the major individual contributory factors to the uncertainty budget will need to be controlled at the 100 nm level.

Contact measurement and inspection remain very popular processes for the conventional dimensional control of the production of mechanical components. They provide appreciably robust, cheaper single-point control, and more tolerant of some types of contamination with reasonable accuracies compared to the non-contact dimensional inspection processes. So, it seems very unlikely that the demands for them will show a notable decrease, at least over the coming decades. An increasing demand for improving the accuracy performance of contact inspection instruments seems inevitable. This implies that advanced mechanical and electronic systems are to be implemented in their designs.

In recent years, many of the manufacturers of contact probe instruments have produced some sophisticated models with advanced design technologies and improved measuring accuracy and precision in order to cope with the growing needs of industry. To give a typical example, digital electronic indicators appeared as a result of the limited measuring performance of the mechanical dial indicators at the level of high precise measurements. The authors in [2] stated that most digital indicators already offer 1 μm resolution, and 0.5 μm resolution is readily available. In contrast, few mechanical dial indicators resolve finer than 1 μm. Digital gauging amplifiers offer 0.1 μm resolution, and some transducers are capable of such accuracy. They expected that improvements in transducer technology over the next few years will allow gauges to combine high resolution accuracy of better than 1 μm with long range of larger than 25 mm.

The authors also pointed out that as dimensional tolerances become tighter, surface finish and geometric variations represent a larger proportion of the total allowable part variation, and their measurement becomes increasingly important. As production requirements demand more complex measurements, gauge makers will respond with sophisticated gauges to do more work for the user. Increased data storage and processing power will be built into gauges, and more gauging functions will be built into computers. Computer-aided gauges will guide procedures and setups, establish datum and compensate or account for geometric and environmental variation. The authors concluded that the future of contact-style dimensional gauging will be largely a process of computerizing many tasks that currently are performed with mechanical instruments: some (or perhaps many) complex routine inspection and measurements tasks will become easier, more precise and/or quicker to perform. Gauges will be integrated increasingly into feedback-controlled manufacturing processes and into company-wide networks. Overall, gauging will play an even more important role than it does today in quality-oriented product development and manufacturing.

This simple example reveals in general terms the future of contact-gauging processes. It emphasizes the essential development of conventional contact-measuring instruments to accommodate the growth in precision of many technological industries: electronic indicators are the coming era of contact-inspection tools at the level of high precision machine shops and quality control checkpoints. Moreover, the authors gave a clue to the importance of surface finish in the contact-gauging processes as smaller dimensional errors are allowed. They stated in [3] that a new quality issue has arisen as dimensional tolerances have decreased: factors of part geometry and surface roughness, once so subtle that they could previously be ignored, are becoming increasingly important. Hence, it seems from these two articles that manufacturers of displacement gauges are already concerned about the significant effect of surface quality on the contribution of errors to measurement. Manufacturers rarely provide information beyond the features of their instruments; they sometimes assist users through general guidelines for the optimum option to accomplish the required measurements within the instrument accuracies. Users' full awareness of this effect is questionable as manufacturers' recommendations do not usually go that deeply into details.

2. Potential Errors in Indicators

Indicator gauges are delicate instruments and the amount of satisfactory service that they will give depends to a very large extent on the way they are used [4]. In general, the higher the magnification the more delicate they become. In dial indicators, as in any mechanical device, friction, dimensional tolerances between parts and wear may cause eventual loss of sensitivity and accuracy [5]. In addition, motion of sensing element leads to problems with hysteresis, non-linearity and temperature variation.

In normal operation, potential sources of error from the internal mechanism of the dial indicator include: (a) the gear teeth mesh with some clearance, causing backlash and lagging response, particularly when wear progresses, (b) the effect of imperfect gear form, or play, results in cumulative error, which is usually proportional to the length of the gauging travel, (c) a clearance of the measuring spindle in its guides is needed to prevent binding and to provide an unimpeded operation movement; this clearance can result in positional variations of the rack in relation to the meshing pinion, (d) play in the pivot bearings due to initial inaccuracies or wear affects the precise meshing of the gear teeth, causing measuring errors [6]. Hence, such errors mainly cause two functional deficiencies, which are (1) lower accuracy if it is used over the whole range of travel and (2) slight variations between forward-moving-spindle (or upward) and backward-moving-spindle (or downward) readings. The electronic indicator may also suffer from the second deficiency which could be as a result of the error source in (c) above.

2.1 Effects of Spring Rate and Friction

The force of the pullback spring, which is needed to keep the contact tip constantly in touch with the workpiece, is not uniform along the range of the spindle travel, as with the behaviour of any spring mechanism. The spring force is designed not only to maintain contact but also to overcome the total friction between the different moving components (e.g. at gears' joints) and between the dirt-extracting elements (wiping seals) and the spindle. Thus, the variation of the resultant force exerted on the spindle is not linear with its displacement. Additionally, such force causes bending and compressive strains in the metrology loop of which the joints, gear-train, spring, and spindle are parts. The determination of the magnitude and variability of these strains and their contribution to the error budget of the indicator seems to attract little interest from researchers or industry, probably, because the calibration processes have been thought sufficient for providing the required final measuring accuracy of the indicator.

2.2 Thermal Effects

Another very important source of mechanical errors in such indicators is the thermal effects. Typical workshop temperature variations (of ±5 ºC or more) can have a significant effect on the accuracy of these instruments, particularly if the rate of change is significant (greater than 3 ºC/hour). A steel spindle of an indicator of 100 mm long (with a typical thermal expansion coefficient of 12×10^{-6} ºC^{-1}) the change in length for a temperature change of 5 ºC is about 6 μm [7]. In the same way, the thermal expansion in gears diameters and their centre distances can be determined. These expansions (and probably more from other components) interact with each other to result a variable backlash error with temperature and, in turn, affect the indicator's measuring accuracy. Therefore, continuous inspection tasks using high-accuracy indicators are supposed to take place in a temperature controlled environment to minimise these thermal effects.

2.3 Effect of Interchanging Contact Tips

Manufacturers of dial and electronic indicators commonly offer the feature of interchangeable contact tips on them, for purposes such as maintenance, application, etc. The contact tip is usually mounted at the free end of the indicator's spindle by means of a screw thread. This means that an additional source of uncertainty is created in the metrology loop. In other words, the compliance of the tip mount (screw threads interaction) is also expected to contribute displacement errors to the indicator readings. These errors could introduce a gross adverse effect if, for example, an unstable mounting (insufficient tightening) of the contact tip is accidentally attained. It is considered one of the genuine characteristics inherent in indicators as the above sources of error.

Electronic indicators also suffer from all of the above sources of error because of the mechanical system that couples the electronic transducer to the workpiece. Although, this mechanical system is of shorter span within the metrology loop than that of the dial indicator, errors due to strain, friction, and thermal effects are still inherent in it. The electronic transducer itself has inherent errors such as linearity, electronic noise, and digitisation; and can also be vulnerable to environmental noise and thermal effects. With the exception of non-linearity, these potential errors of a well-designed transducer are likely to have considerably smaller effects on measurement compared to those of the mechanical system.

3. Force Data Provided By Manufacturers

The variety of needs of indicators' users has lead manufacturers not only to produce a variety of indicators of different accuracies and travel ranges, but of different measuring forces, as well. Gauging highly compliant surfaces needs indicators of low measuring forces in order to attain the required accuracy and stability of measurement. Indicators designed with pullback spring mechanisms, such as all of the dial gauge and most of the electronic gauge indicators, have the normal spring rate effect which introduces a distinctive and systematic variations of spring response with displacement. So, the probe rod of these indicators usually presents its maximum gauging force when it is nearly in full retraction. Since, the rod movements in dial indicators is governed by the rack and gear-train movements in addition to the friction and spring forces, the Earth's gravitational forces are usually considered of negligible effect on the gauging forces. Dial indicators are commonly used in any direction (vertically, horizontally, upside-down, etc.) and their manufacturers do not associate their measuring forces with any specific attitude of operation. We observe that they normally provide one value only for these forces which is sometimes unclear whether it represents the average or the maximum gauging force.

Some manufacturers specify fuller information for only those types of electronic indicators which are meant in their designs to offer the reduced gauging pressure feature. The probe rods of electronic indicators are generally ballbush- or slide-guided and secured only by much lower magnitudes of pullback spring and friction forces compared to those of the dial ones. The weight of the probe rod, and its associated components that move with it, tend to either aid or oppose the spring force depending on the orientation of the indicator gauge. So, when such indicators are in vertical-downward use, the resultant measuring force will be in its maximum regime. The opposite would be true if they are in vertical-upward use. If they are used horizontally, these forces are in their average regimes. Thus, in general, the gauging force of the spring-type electronic indicators are not only affected by the spring rates, but also influenced by the operating orientation of the indicator gauge. A few of the manufacturers of such indicators give more attention to this issue and show further details, such as the measuring forces in different attitudes of operation.

As mentioned earlier, the friction forces from the gear-train mechanism and its joints (in dial indicators), bearings, and wiper affect the spring rate behaviour. This results in uncertainties in the "varying" gauging force along the travel range of the probe rod. Moreover, the interaction between the rod and the wiper is, in practice, sensitive to the direction of movement. The wiper is a kind of dust seal used to repel dirt from outside the gauge and, hence, needs to exert more forces on the probe rod as it retracts inside the gauge. As a result, the rod produces greater forces along the inwards direction than along the outwards direction, and a force hysteresis could be developed over one complete stroke of its travel. Even if the sliding force at the seal is consistent, there will still be a hysteresis effect in the contact force. At the instant the probe ceases to move, the friction will be in the opposite direction to that movement. It is unlikely that the friction force will reduce to zero once movement stops due to the static force. If lower contact forces are needed, the last direction of movement of the rod, before establishing contact, should be outwards. We also observe that only a few of the manufacturers publish information about this friction-derived hysteresis for either the force or displacement.

4. Force Measurement on Real Indicators

To demonstrate the typical behaviour of the indicator's measuring force along the travel range of its rod, three linear high-accuracy dial and electronic indicators were tested. These are: a John Bull (British Indicators Ltd.) dial indicator (model: 2U, accuracy: unknown, resolution: 2 µm), a Mitutoyo Digimatic series 543 electronic indicator (model: ID-F125E, accuracy: ±3 µm, resolution: 1 µm), and a Heidenhain digital length gauge (model: MT30, accuracy: ±1 µm, resolution: 1 µm). All the three gauges had been used regularly and so were regarded as typical of 'working' instruments rather than being as-new ones. For convenience in this context, these indicators were given the codenames: G1, G2, and G3, respectively. The

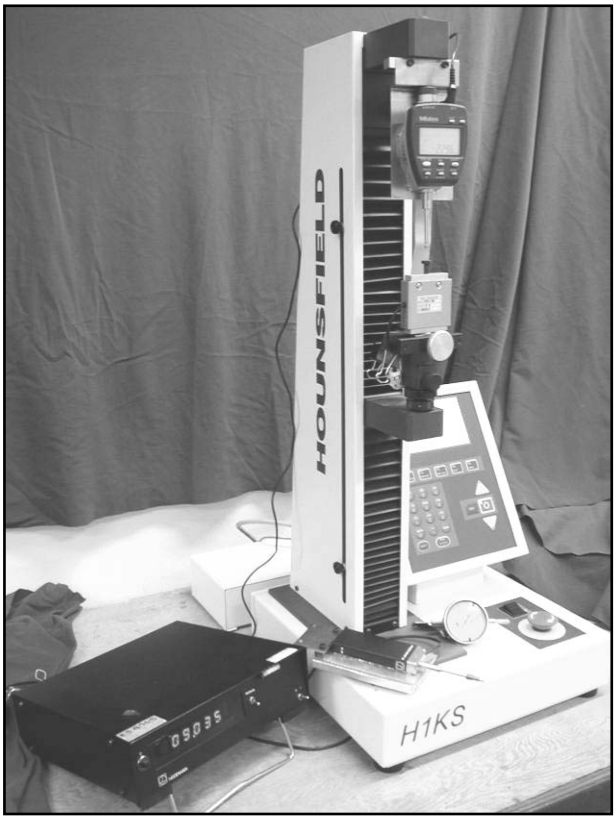

Figure 2
The setup used for measuring the gauging force of the three available dial and digital gauge indicators using the Hounsfield Test

force measurement of the probe rods was accomplished with the Hounsfield Tensile/Compressive Test Equipment (model: H1KS, accuracy: ±25 mN in force, ±10 µm in displacement) which is regularly calibrated to meet the industrial standards. Each indicator was mounted on the top fixed head on the stand of the Hounsfield system, as shown in Figure 2. The force transducer was clamped on the motorized head (crosshead) on this stand and was, then, pushed and pulled during measurement against the indicator's probe rod using the system's controls. The displacement readings of the Hounsfield system crosshead were also collected to be compared with those shown by the indicators.

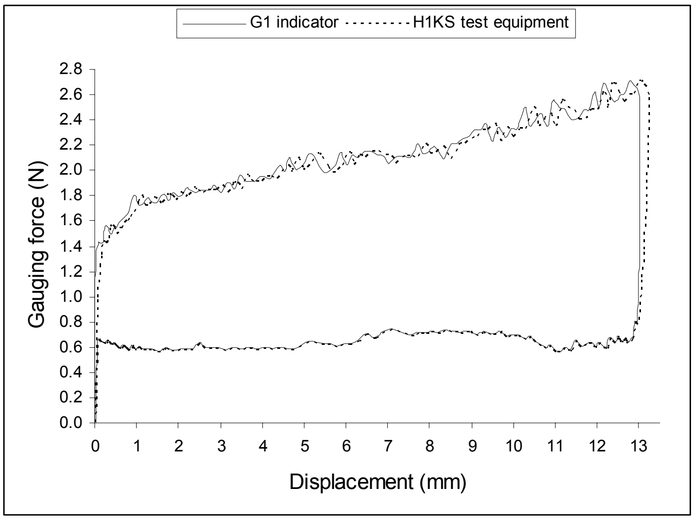

Figure 3
Force hysteresis measured along the travel range of the probe rod of the G1 indicator

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Figures 3, 4, and 5 illustrate the hysteresis of the gauging force measured along a complete return travel of the probe rods of the G1, G2, and G3 indicators, respectively. The systematic effect of the spring rate was clearly shown by all of these indicators in both directions of travel, in addition to the distinctive effect of the wiper friction. Moreover, relatively minor variations of this force, mainly due to the combined effect of the stick-slip friction forces from both the bearing and wiper, were also noticed superimposed on the general trends.

The G1 indicator showed a maximum uncertainty in its contact force of around 2 N (Figure 3). Although there is no information available about the manufacturer's measuring force of this indicator, compared to a rival one from Mitutoyo, for instance, it has much less measuring force. This figure shows an increasing displacement error along the upwards travel of its probe rod, which reached to more than 230 µm at the end of the travel range where the maximum force regime is nominally located. At the onset of downwards travel of the rod and during the rapid decrease in its force (due to the change of magnitude and direction of the wiper friction force), this displacement error decreased back (because of reversing the rod motion) to its initial magnitude. Along the downwards travel of the probe rod, the differences between the two displacement readings were below 55 µm. While there is some evidence of a calibration divergence between the gauge and the Hounsfield and there may also be a cyclic error in the gauge, the magnitude of the errors correlates with increasing force. The different manufacturing tolerances and wear processes within the gear-train may have influenced this increase (or decrease) of such error along the travel range. The higher forces may directly introduce errors by straining the gauge mechanism and may also cause higher wear.

The G2 and G3 indicators showed much lower uncertainty in their contact forces than the G1 indicator. The maximum magnitudes of their gauging force were observed to be within the values provided by their manufacturers, with maximum uncertainties of about 0.9 N and 0.5 N, respectively. The rod displacement error was also noticed on these two indicators, but with much lower maximum magnitudes and at different locations in the hysteresis loop. Along the upwards movement of the rod, the G2 indicator produced its maximum displacement error of nearly 120 µm between 3 and 6 mm of rod displacement: the region has higher and more variable contact forces than normal (Figure 4) presumably due to high friction forces. The G3 indicator revealed approximately 90 µm maximum displacement error within the 4 to 8 mm region which has the highest contact forces (Figure 5). Similarly to the G1 indicator, at the start of downwards movement of the rod and the large change in its force, this displacement error decreased and, along the downwards movement of the rod, the maximum differences between the displacement readings did not exceed 75 µm and 45 µm on the G2 and G3 indicators, respectively. When considering gauging over only a limited region of travel in this direction, the relative deviations in displacements are obviously far less than the maximum ones. However, this should easily be recognised through the calibration processes that should be carried out regularly on any indicator to certify its serviceability.

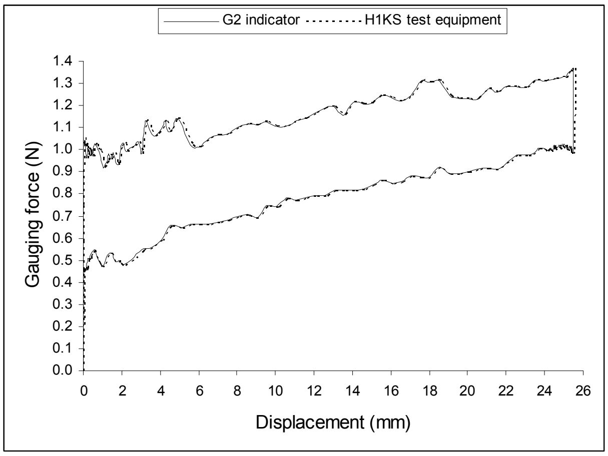

Figure 4
Force hysteresis measured along the travel range of the probe rod of the G2 indicator

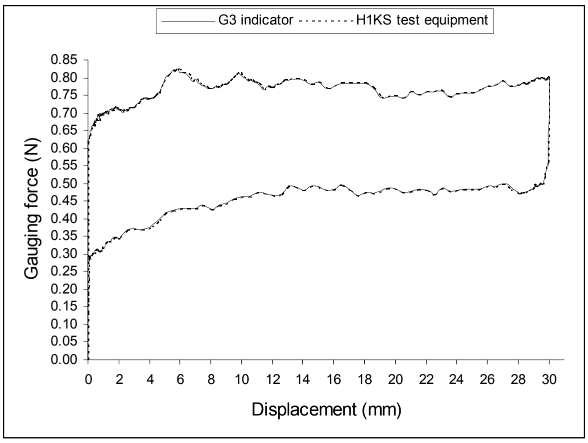

Figure 5
Force hysteresis measured along the travel range of the probe rod of the G3 indicator

5. Discussion

In many modern designs of precision indicators, the wiping seal is replaced by an external corrugated rubber cover that conceals the rod surface in order to reduce the force uncertainty due to the friction-derived hysteresis. In some designs of electronic indicators of high accuracy, the gauge head is also equipped with a motorised or a pneumatically-controlled plunger to eliminate the spring rate effects, as well. However, effects of the force contributed by such stretching cover to the resultant gauging forces could also be of notable magnitudes. In addition, the measuring (or approach) speed of the contact probe, towards the surface to be gauged using indicators with controlled probe rods, could be a new significant parameter, since it may lead to additional plastic deflections on the surface due to the impact.

The resultant interaction between the different inherent forces in the indicator mechanism is becoming increasingly important in evaluating the error budget of the complete gauging process. When high precision comparative measurements are to be achieved on surfaces of different characteristics, the contact force uncertainties of the indicators used obviously generate significant uncertainties through the deformation at these surfaces which, consequently, affect the final accuracy of such measurements. To give exaggerated estimates for such deformations on perfectly smooth surfaces using the Hertzian contact analyses, a 3 mm diameter probe tip with an average gauging force of 2 N could cause indentation depths of 0.5 μm and 0.8 μm on steel and aluminium surfaces, respectively. These deflection values will at least be doubled on such surfaces if a moderate roughness of just around 0.2 μm is considered on them. Hence, a contact force uncertainty of 0.5 N could additionally lead to variation in deflections in the micrometre range on such surfaces.

Among the experienced users of indicators, it might be well-known that, in high precision measurements, probe rods are recommended to be brought gently into contact with surfaces during their downwards (return) travel in order to avoid those regions of the high gauging forces and backlash errors. In practice, using indicators with small ranges of travel (2 mm or below, for instance), which are usually chosen for such purposes, makes it difficult to guarantee that adjustment in the recommended way occurs in every location of measurement. So, the maximum uncertainty in contact force is still of a potential effect in gauging with these indicators, in addition to the uncertainty in displacement. This is also possible in absolute measurements with digital indicators, such as the G2 and G3, where both probe rod directions of movement could be involved.

6. Conclusion

The different sources of error in the internal mechanism of the indicators have been discussed for the purpose of highlighting most of the potential uncertainties involved in the measurement with such instruments. Tests performed on the three serviceable high-accuracy indicators revealed the systematic effects of spring rate, a substantial force difference between the two directions of movement of the rod, stick-slip friction forces of the rod bearing and the wiper, and a displacement error at, broadly, the maximum force regime of the hysteresis loop. In regard to the increasing demands of industry for tighter dimensional tolerances, these systematic and scattering errors are expected to contribute significantly to gauge error budget, but their analysis has received little attention from researchers.

An additional uncertainty has been considered in this investigation, which is induced by the complex contact interaction between the probe tip and the engineering surface. Depending only on elementary contact analyses, force uncertainties encountered in our tests have been noticed capable of generating contact uncertainties well above the 100 nm level of concern. Further experimental investigations on the uncertainty of contact of probe tips have confirmed this fact on most common conditions of engineering surfaces.

Most manufacturers of indicators have been observed not to pay much attention to providing detailed force characteristics for their precise models. General guidelines provided by few of them to the users (for selecting the proper gauge for the measurements to be done) do not strongly emphasize the measuring force as a criterion for selection. Since the manufacturers are already aware of the effect of surface roughness on the contact measurements, we suggest that these guidelines should also include recommendations on the permissible limits of surface material and finish for each gauge model beyond which uncertainties from the contact interaction can be significant in the error budget.

Acknowledgement

The authors would like to express their sincere thanks to Prof. D. G. Chetwynd (Centre for Nanotechnology and Microengineering, School of Engineering, University of Warwick, Coventry, UK) for his support, guidance and suggestions which lead to formulate some of the results presented in this paper.

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