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Modeling the effect of probe force on length measurements on polymer parts

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Abstract
Measurement uncertainty at micrometer level is in the future going to be very common in dimensional measurements on polymer parts. Accurate dimensional measurement of polymer parts is becoming a key and common practice in the industry, especially when micrometer tolerances are required. When conducting measurements with a contact probe there is always a force applied to the part. This force (0.3N – 3.3N) leads to deformations that an influence the final result. The unknown deformation of the part under the measurement conditions can produce significant errors in the measurement. In the present work, Hertzian contact theory was applied to find the deformation analytically, where the measuring force was imposed to the part. Material properties of the polymer and radius of the probe tip were known parameters. The finite element software ABAQUS was then used to model the contact problem numerically. Both analytical and numerical approaches were compared with the experimental results. The results showed that the numerical model was able to predict the deformation of the polymer part due to different probe forces. Furthermore it was shown, that the probe force should be taking into account when measurement with a few micrometer accuracy should be performed on thin walled polymer parts.

Metrology, Measurement force, Modelling.

1. Introduction

When speaking about measurement at micrometer level in polymer parts, the measurement procedure must be defined such that the measurement instrument doesn't influence the dimension of the part. The contact probe which is very common in measurement can have side effect to the parts in accurate measurements because of the relatively low mechanical stability of polymers after production (compared to metals). The effect of probe force on geometry is therefore important to consider when accurate measurements are needed [1]. The probe can be modelled by using analytical calculations or finite element analysis to find its interaction with workpiece and obtain more accurate measurement as performed by Feng et al. [2-3]. In the present study the effect of the probe force on the length dimension of a polymer sample is investigated by Hertzian contact theory and finite element analysis.

The next section addressed the experimental study. The analytical approach for deformation due to contact probe force is investigated in section 3. In section 4 the numerical solution is conducted by using a finite element analysis. Results which were obtained from previous sections are analysing in section 5. Finally the last section concludes the paper.

2. Experimental Study

The setup for the experiment allows the measurement of the length of a polymer part when applying force in a range of 0.3N – 3.3N. The measuring device is a linear actuator (SMAC LCA 25-010-52F3) with a resolution of 0.1 µm. The support for the specimen and the probes is made of Invar. The specimen is an ABS part with a complex geometry and thin walls. The length measurements at different force levels were repeated 10 times for 5 parts. The experimental results for length variation are obtained as shown in Table 1. The measurements were performed at a constant temperature of 20˚C.

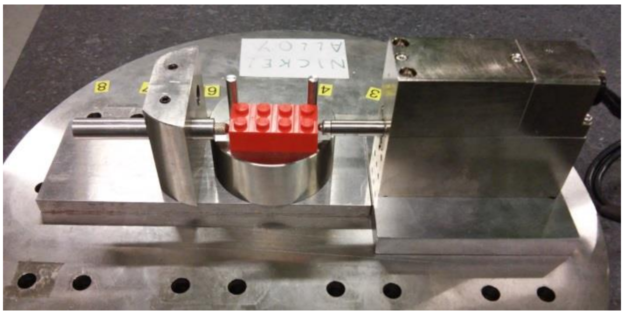

Figure 1. Experimental setup: Measurement of sample length with a SMAC probe.

3. Analytical solution

The deformation caused by the probe force can be calculated by Hertzian contact theory [4]. The assumptions for this theory are 1) The surfaces are continuous and non-conforming, 2) The radius of contact probe is much larger than radius of the circle of contact (a<<R), 3) Each solid can be considered as an elastic half-space, 4) The surfaces are frictionless. The contact conditions are schematically is shown in Figure 2 and equations (1-3) is used to calculate the deformation.

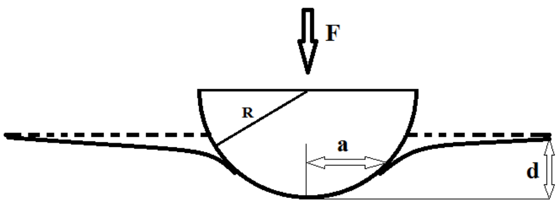

Figure 2. Contact of a rigid sphere with an elastic half-space

$$E_p^* = \frac{E_p}{1-(\upsilon_p)^2} \qquad (1)$$

$$a^3 = \frac{3FR}{4E^*} \quad (2)$$

$$d = \frac{a^2}{R} \quad (3)$$

Where E_p is Young's modulus and ν_p is Poisson's ratio for the polymer. E_p^* is the equivalent Young's modulus. F is the applied force by measurement the probe, R is the radius of probe, d is deformation and a is the radius of deformation.

The results from the analytical solution are shown in Table 1. As it is observed, they are not close to the experimental results because of the low thickness of the part's wall. In next section a numerical analysis is conducted which can provide more information about effect of probe on the polymer sample by including probe position.

4. Numerical solution

The polymer part is numerically modelled in ABAQUS. The material is ABS (acrylonitrile butadiene styrene) which is assumed to be isotropic. The probe is considered as a rigid body. As seen in Figure 3, six positions are defined for the probe to be placed in order to find out why the analytical solution is different from experimental result. For the experiment, the probe was placed at position 5. The results from the numerical model in terms of the length variations for all the positions are listed in Table 1.

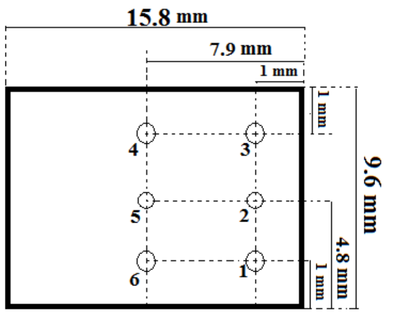

Figure 3. Schematic illustration of the probe positions in simulation.

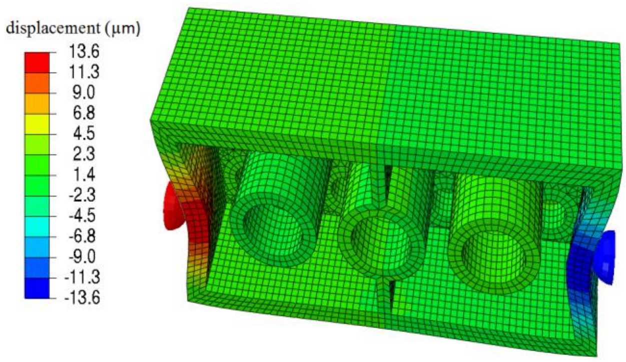

Figure 4. Contact simulation in ABAQUS, displacements in the direction of force (2.01N), the deformation is exaggerated 100 times.

5. Result and Discussion

For better comparing the results, all of the length variations as a function of probe force are plotted in Figure 5. The numerical results show the probe is close to position number 6 instead of 5. This error can be solved by using more accurate values for force and Young's modulus.

The analytical results are close to probe positions 1-4. In Hertzian contact theory the sample should be rigid enough (position 1-4) to have only the deformation due to contact but in position 5 and 6, the force causes bending as well, which cannot be calculated by Hertzian formula. Therefore in the middle of the polymer part where the part is hollow, the analytical solution is different from experimental result.

If this probe is used to find the deformation due to other phenomena such as temperature or moisture in micrometer level, the deformation because of the probe force will be considerable.

The probe has minimum deformation on position 2, where it can be used for future measurement of other phenomena.

Table 1. The length variation for probe force (experimental , analytical and numerical)

Force (N)	Exp. (µm)	Ana. (µm)	Numerical (6 positions, µm)					
			1	2	3	4	5	6
0.3	2.5	1.6	1.1	0.6	0.6	0.7	1.9	4.7
0.7	6.4	2.4	2.0	1.1	1.1	1.2	3.5	8.8
1.0	10.1	3.1	3.0	1.6	1.7	1.8	5.1	13.0
1.3	12.3	3.7	3.9	2.1	2.2	2.4	6.8	17.2
1.7	18.8	4.3	4.9	2.7	2.7	3.0	8.4	21.3
2.0	22.0	4.8	5.8	3.1	3.2	3.5	10.0	25.2
2.3	25.5	5.3	6.7	3.7	3.7	4.1	11.6	29.2
2.6	29.2	5.8	7.7	4.2	4.3	4.7	13.2	33.4
3.0	31.5	6.3	8.6	4.7	4.8	5.3	14.9	37.4
3.3	35.6	6.8	9.5	5.2	5.3	5.9	16.5	41.7

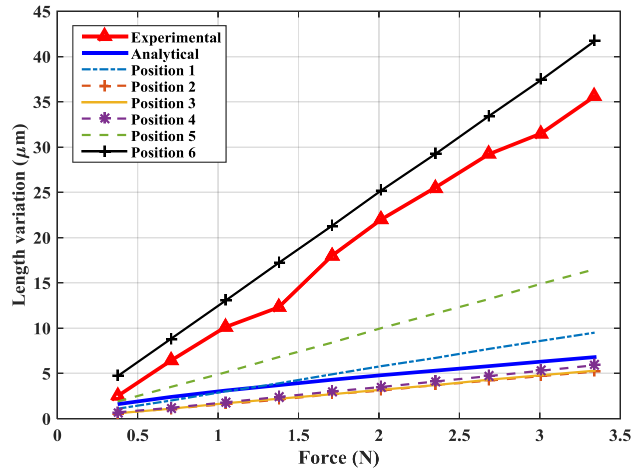

Figure 5. Comparison of the length variation as a function of probe force found experimentally, analytically and numerically, respectively.

6. Conclusion

The conclusion of this study can be summarized as follow:

1. The deformation of the part has a significant effect on accurate measurement of polymer parts, from a few micrometres to 40 µm depending on the probe force.
2. The determination of the measuring conditions and the force compensation is an essential factor for accurate measurements.
3. It is essential to provide the finite element model with the accurate material properties and force to obtain the numerical results exactly the same as the experimental results.
4. The probe force effect can be calculated by Hertzian contact theory where the part is rigid and the theory's assumptions are met.

References

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