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EXPERIMENTAL DETERMINATION AND FORMULATION OF MATHEMATICAL MODEL FOR CONTACT DEFORMATION OF NYLON AND PVC

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ABSTRACT

The surfaces of the most engineering materials are unavoidably rough and contain geometric irregularities with feature sizes ranging over many length scales. The contact between rough surfaces is generally restricted to the tips of asperities. Consequently even a light mechanical load can cause localized surface plastic deformation and residual stress will be developed after unloading. The point contact between asperities renders the contact area negligibly small and can be considered tending to zero. This implies stress at point of contact is infinite even under influence of light mechanical load. This infinite stress is responsible for material flow and consequently results in micro displacement. This phenomenon is called contact deformation. Micro displacement errors due to contact deformation and dimensional instability in members of precision machine tools like CNC's are highly intolerable. The scope of present work is an experimental study in effect of load and surface roughness on nylon and polyvinyl chloride and the results analyzed to obtain a general equation. The mathematical model so developed is based on statically designed experiment.

Keywords: *Contact Deformation, Nylon, PVC.*

1. Introduction

Micro displacement errors in members of precision machine tools like CNC's are highly intolerable. The major source of such errors is contact deformation and dimensional instability. Good design is important for any manufactured product but for plastics it is absolutely vital. Most of those we use today have been around for little more than two generations. Compare that with the thousands of years of experience we have with metals. Plastics and Composite materials have been excellent substitute for traditional materials for their tamed frictional behavior. Plastics increasingly replace traditional materials such as bronze, stainless steel, cast Iron and ceramics. They are chosen for improved performance and cost reduction.

Plastics can:

- Reduce Weight
- Eliminate Corrosion
- Improve Wear Performance in Unlubricated Conditions.
- Reduce Noise
- Increase Part Life
- Insulate and Isolate Thermally
- Insulate and Isolate Electrically
- Plastics expand and contract 10 times more than many metals.

A material's dimensional stability is affected by temperature, moisture, absorption and load. Assemblies, press fits, adhesive joints and machined tolerances must reflect these differences. Certain plastics such as nylons are hygroscopic, absorbing up to 8% water (by weight, when submerged). This can result in a dimensional change of up to 3 %. Plastics inherently lower modulus of elasticity can also contribute to dimensional change including part distortion during and after machining.

The advantage of filled plastics is that the overall properties are superior to those of individual constituents. The properties that can be improved during the formation of such composite materials usually include, but are not limited to: strength; stiffness; corrosion resistance; surface finish; weight; fatigue life. In recent decades, due to high strength-to-weight and stiffness-to-weight ratios, fiber-reinforced plastics have been extensively used for many applications, such as machine tools industry, aerospace structures and high speed turbine machinery. Accordingly, mechanics of fiber-reinforced plastics has been intensively studied and handbooks guiding the design and testing have also published. Till today there is a dearth of design data, for experimental evaluation of contact deformation.

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The present research is concerned with the evaluation of contact deformation of nylon and polyvinyl chloride.

The contact deformation behavior of nylon and polyvinyl chloride was studied under the influence of Load and surface roughness.

Filled or unfilled plastics are affected by:

- Working in an environment, wherein the interface temperature has tendency to rise up to 150°C and Working in a humid atmosphere
- Different loading conditions
- Different surface roughness

Life and durability of such guide material considerably under these two specific conditions. Moreover the temperature at the interface may result in thermal deformation of the slides or and this, in turn, affects the microdisplacement.

2. Scope of the Work

An experiment to study effect of load and surface roughness on nylon and polyvinyl chloride was performed and a quantitative model for contact deformation of the same was formulated. The mathematical model so developed is based on statically designed experiment.

2.1 Motivation behind the work

The motivation behind this research is to generate a method to create database for different materials which would be useful for professional engineers and machine tool designers in designing of critical components of machine tool members like guide ways as in case of CNC machines.

2.2 Contact deformation

The surfaces of most engineering materials are unavoidably rough and contain geometric irregularities with feature sizes ranging over many length scales. The contact between rough surfaces is generally restricted to the tips of asperities as shown in Fig.1. Consequently, even a light mechanical load can cause localized surface plastic deformation and residual stressed will be developed after unloading.

Stress can be expressed as:

$$\sigma = force \,/\, area \qquad (1)$$

The point contact between asperities renders the contact area negligibly small and can be considered tending to zero. Hence,

$$\text{Stress} = \frac{Force}{Area \to 0} = (\sigma \to \infty) \qquad (2)$$

This implies stress at point of contact is infinite even under influence of light mechanical load. This infinite stress is responsible for material flow and consequently results in micro displacement.

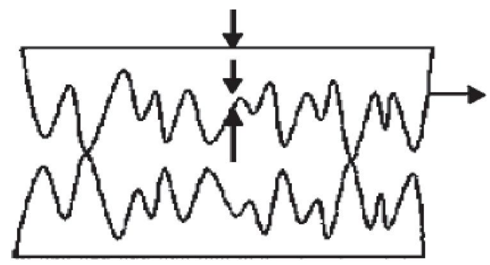

Fig. 1 Surface Asperities in Contact

Even though the base material is in elastic limit, the surface layer deforms plastically up to certain extent. The study of plastically and residual stresses of rough surface contacts is of critical importance in understanding friction, wear, contact fatigue and many other surface failure phenomena.

2.3 Materials selection

Plastics are commonly described as being either a thermoplastic or a thermoset. Thermoset materials such as phenolic and epoxy were developed as early as 1900 and were some of the earliest “high volume”. Both thermoplastic and thermoset stock shapes are available for machined parts, although thermoplastic stock shapes are much more commonly used today. Their ease of fabrication, self lubricating characteristics and broad size and shape availability make thermoplastics ideal for bearing and wear parts as well as structural components. The material selected for the purpose of sample experimentation carried out on the fabricated test rig was nylon and polyvinyl chloride.

3. Experimental Determination of Contact Deformation

An experiment is one of the most important aspects in engineering to generate practical data, to appreciate and visualize complicated concepts, behavior of material, processes, etc.

3.1 Objective of the experiment

The objective of experiment is to mathematically express Pressure and Surface roughness as a function of contact deformation. The material considered is Nylon and PVC. An important aspect is the mode of deformation of the containing asperities, that is, weather all the peaks deform elastically, crush plastically, or pass through a complex mixture of these two modes. Whatever theoretical analysis is done, the following assumption must hold true.

i) Contacting surfaces are isotropic.
ii) Asperities may be taken as spherical.

3.2 Design of experiment

Experimental design involves planning experiments to obtain the maximum amount of information from available resources. A factor is a variable that may affect the response of an experiment. In general, a factor has more than one level.

A factorial design is used in experiments involving multiple factors, where it is necessary to study joint effect of the factors on a response. A potential concern in the use of two-level factorial design is the assumption of linearity in the factor effects. Perfect linearity is unnecessary.

There is a method for replicating certain points in 2^K factorial that will provide protection against curvature of second order effects as well as allows an independent estimate of error to be obtained. The method consists of adding center points 2^k design. Two factors each at two levels make it $2^2 = 4$ experiments. Two center points are considered thus adding the total number of experimental runs to 6 per material. The Coding of the parameters at two levels for the above runs is as follows:

- High level of a parameter denoted by '+1'
- Center point of a parameter denoted by '0'
- Low level of a parameter denoted by '-1'

Let, Ra represents surface roughness,
P represents pressure,
$\delta_{c \text{ represents}}$ contact deformation.

Table 1: Design of Experiment

S. No.	Ra	P	δ_c	Y=log δ_C
1	-1	-1	δ_{c1}	Y_1
2	-1	1	δ_{c2}	Y_2
2	1	-1	δ_{c3}	Y_3
4	1	1	δ_{c4}	Y_4
5	0	0	δ_{c5}	Y_5
6	0	0	δ_{c6}	Y_6

3.3 Experimental setup

The test rig used for the measurement was indigenously designed and fabricated by Prof. Shah and Dr. S. K. Basu at Govt. College of Engineering Pune. This type of test setup was first devised by Lapidus, which over a period of time, was modified and improved. The simple to operate and inexpensive set up consists of a rigid and heavy base plate adequately thick with hardened and coated surface on which the specimen is kept. The specimen size can be varied as per requirement. For the present work specimen with diameter 32 mm and height 25 mm were considered.

The specimen has an internal diameter of 10 mm. An EN-31 disk is mounted on the top of specimen. On the top of the disk at center a hardened steel ball is mounted which supports the fulcrum lever on the top. The fulcrum lever carries dead weight, which transfer the load on the specimen through a steel ball. An extension probe touching the-interfacing surface of the EN-31 disc does the measurement of contact deformation. The details of this can be seen in Fig.3. The extension probe passes through the sleeve hacking 8 mm diameter hole all through the base plate and the backup bolster fixed on the setup. This extension probe is mounted on the piezoelectric probe of the TESA probe with the sleeve D.

The sleeve is again fixed with the housing bracket C. The design of the extension rod is such that it will be in contact with the top disc A after passing through the central hole of the specimen at point E while the other end of this will just lie mounted on the end of TESA probe. The extension probe has a limited range of movement between the top face of the disc and TESA probe. The TESA probe may get damaged at elevated temperature and hence cannot be directly interfaced.

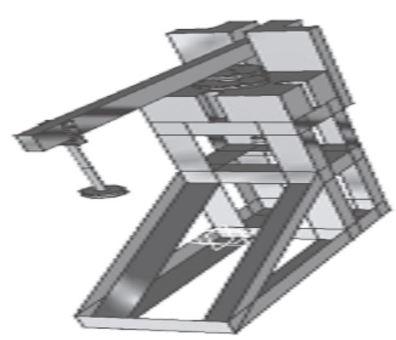

Fig. 2 Contact Deformation Evaluation Test Rig

3.4 Equipment and accessories used

- Portable roughness tester 'MITUTOYO'.
- Electronic linear gauging instrument with analogical readout.
- TESA make Electronic comparator with least count 0.01 micron.
- Spirit-level for ensuring proper level of Test rig

4. Experimental Procedure

i. Level the Test rig with the aid of spirit level.
ii. Arrange the specimen into different groups according to their surface roughness values and

number/ code them. The groups have been subjected to respective surface roughness.

iii. Arrange the weights according to requirement. For conducting experiments for determination of inherent damping coefficients arrange the weights in order of 1Kg, 2Kg, 3Kg, 4Kg, 5Kg, respectively. Care should be taken that the weights should be added / removed in succession of 1Kg only and NOT BE REARRANGED (i.e. the weights should not be removed once placed on test rig, to increment / decrement to next level).

iv. Keep sheets ready for recording the results of experiments. Tabulate the sheets for ease in recording data.

v. Once the specimen is placed, put the EN-31 disk and adjust the zero setting of TESA Probe.

vi. Once the zero is set. Load the test rig; allow the indicator of comparator showing deformation reading to stabilize. If reading goes out of range adjust the scale of the comparator. Now record the appropriate reading.

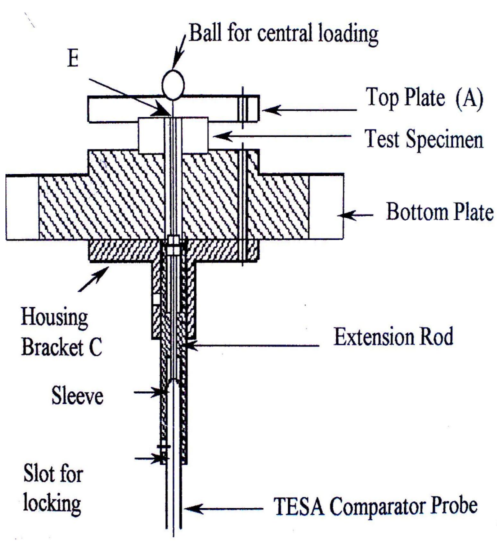

Fig. 3 Contact Probe Assembly

Fig. 4 Portable Roughness Tester

Fig. 5 TESA Electronic Comparator

5. Experimental Observations and Analysis

Using the Contact Deformation set-up, as discussed in detail earlier, the comparator reading shows that the total deformation of two surfaces in contact. This total deformation is calculated and subtracted from the total deformation to get the exact value of contact deformation and is expressed in the form of equation:

$$2\delta_c + \delta_e = \delta_{total} \quad (3)$$

Where,

δć – Contact deformation on one face of specimen.
δe – Elastic deformation
δt – Comparator reading (total deformation)

$$\delta_c = \frac{\delta_t - \delta_e}{2} \quad (4)$$

$$\delta_e = \frac{P \times t}{AE} \quad (5)$$

Where

δe – Elastic deformation
P – Load acting on the interface in normal direction
E – Young's module of the specimen
A – Surface area of the specimen
t – Thickness of the sample.

Consider the lever to be in equilibrium. Sum of all vertical forces is zero and sum of all horizontal forces is zero. Sum of all moments is zero.

$$\sum Hf = 0$$
$$\sum Vf = 0 \text{ and}$$
$$\sum M = 0 \quad (6)$$

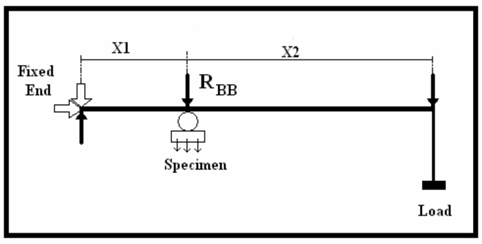

Fig. 6 Reaction Forces Consider on the Horizontal Bar at Various Points

Taking moment about fixed end,

$$(R_{BB} \times X1) + [L\times(X1+X2)] = 0 \qquad (7)$$

Hence,

$$R_{BB} = \frac{-[L\times 9.81\times(X1+X2)]}{X1} \qquad (8)$$

(Negative sign indicates downwards)
The distances X1, X2 are as follows:
X1 + X2 =750 mm;
X1=120 mm;
X2=630 mm.

Table 2: Calculation of Pressure on the Ball

L (kg)	X1	X1+ X2	R_{BB} (N)	A (mm^2)	P (N/ mm^2)
4	120	750	245.250	1083.849	0.2262
2.5	120	750	153.280	1083.849	0.1414
1	120	750	61.3125	1083.849	0.0565

6. Observation and Calculations for Nylon

Table 3: Coding Of Pressure and Surface Roughness for Nylon

	High	Medium	Low
Pressure (N/mm²)	0.2262	0.1414	0.0565
Surface Roughness (µm)	3.98	3.00	2.01
Code	+1	0	-1

Table 4: Actual Deformation after Subtracting Elastic Deformation for Nylon

Sl. No.	Specimen Code	δt (µm)	δe (µm)	$\delta c = (\delta_t - \delta_e)/2$ (µm)
1	L1	5	0.6215	2.1892
2	L2	10	2.4882	3.7559
3	H1	11	0.6215	5.18925
4	H2	20	2.4882	8.7559
5	M1	15	1.5554	6.7223
6	M2	13	1.5554	5.7223

Table 5: Design of Experiment for Contact Deformation

Surface roughness	Load	Contact Deformation	
RA	P	δc(µm)	Log δc
-1	-1	2.18920	0.364551
-1	+1	3.75590	0.574714
+1	-1	5.18925	0.71510
+1	+1	8.75590	0.94230
0	0	6.72230	0.82750
0	0	5.72230	0.75757

Regression Followed by ANOVA for Nylon

Regression Statistics

Multiple R	0.925014344
R Square	0.855651537
Adjusted R Square	0.759419229
Standard Error	0.103655211
Observations	6

ANOVA

	df	SS	MS	F	Significance F
Regression	2	0.191068155	0.095534077	8.89152043	0.087000673
Residual	3	0.032233209	0.010744403		
Total	5	0.223301363			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%
Intercept	0.692910667	0.042317063	16.37426183	0.000495661	0.526459587
X Variable 1	0.1856015	0.051827606	3.581132055	0.037256469	0.001733192
X Variable 2	0.1154085	0.051827606	2.226776609	0.11233265	-0.111214973

The Values of Constant and Exponents

Material	K	α	β
NYLON	4.93072	0.18560	0.11540

Equation for Contact Deformation for Nylon

$$\delta_{c} = 4.93072\ Ra^{0.18560}\ P^{0.11540} \qquad (9)$$

7. Observation and Calculations for PVC

Table 6: Coding of Pressure and Surface Roughness for PVC

	High	Medium	Low
Pressure (N/mm²)	0.2262	0.1414	0.0565
Surface Roughness (µm)	1.6	1.31	0.505
Code	+1	0	-1

Table 7: Actual Deformation after Subtracting Elastic Deformation

Sl. No.	Specimen Code	δ_t(µm)	δ_e(µm)	δc = (δ_t - δ_e)/2 (µm)
1	L1	5	2.2857	1.998
2	L2	8	3.142	2.998
3	H1	11	5.2857	5.319
4	H2	19	8.642	8.81
5	M1	15	6.964	7.011
6	M2	13	5.964	6.119

The Values of Constant and Exponents

MTRL	K	α	β
NYLON	4.88716	0.200872	0.087925

Equation for Contact Deformation for Polyvinyl Chloride (PVC)

$$\delta_{c} = 4.88716\ Ra^{0.200872}\ P^{0.087925} \qquad (10)$$

7. Conclusion

An experiment has been described for determining the contact deformation mechanism for polymeric materials. The experiments are yielding insights into the physics of the micro-displacement phenomenon and associated damping. This information should prove valuable to designers; professional engineers and researchers attempting to build physics based models.

Table 8: Design of Experiment for Contact Deformation

Surface roughness RA	Load P	Contact Deformation δc(µm)	Log δc
-1	-1	2.2857	0.359019
-1	+1	3.142	0.497206
+1	-1	5.2857	0.723103
+1	+1	8.642	0.936614
0	0	6.964	0.842859
0	0	5.964	0.775538

Regression Statistics	
Multiple R	0.89646927
R Square	0.80365716
Adjusted R Square	0.67276193
Standard Error	0.12514879
Observations	6

ANOVA

	Df	SS	MS	F	Significance F
Regression	2	0.192322587	0.096161294	6.139697891	0.087000673
Residual	3	0.046986657	0.015662219		
Total	5	0.239309245			
	Coefficients	**Standard Error**	**t Stat**	**P-value**	**Lower 95%**
Intercept	0.68905643	0.051091779	13.48664006	0.000881515	0.526459587
X Variable 1	0.20087284	0.062574394	3.210144408	0.048950851	0.001733192

The following are contribution of the work carried and concluding points

- A practical approach for evaluation of contact deformation of a range of polymeric materials is presented. The combine effect of load and surface roughness was studied and following mathematical relations were discussed

  Equation for Contact Deformation for Nylon

  $$\delta_{c} = 4.93072\ Ra^{0.18560}\ P^{0.11540}$$

  Equation for Contact Deformation for PVC

  $$\delta_{c} = 4.88716\ Ra^{0.200872}\ P^{0.087925}$$

- The equation can be useful to deduce micro-displacement errors arising out of contact deformation and hence can be important criteria for selection of material.

- Contact deformation is depending on specific pressure on interfacing surface and the centerline average value of surface roughness.
- Under the heavy loading of peaks of the asperities undergo inelastic straining, resulting in flattening of these peaks to the valleys.
- It is possible to state the variation of the contact deformation with the variation of surface roughness is the most significant as compared to the same with the variation with the pressure.
- While noting the experimental observation, it is found that the loading needs to persist for considerable time to record the contact deformation.

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