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**A NATIONAL MEASUREMENT
GOOD PRACTICE GUIDE**

No. 86

Predicting and measuring
the 'feel' of soft-touch
thermoplastic elastomers



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Predicting and Measuring the ‘Feel’ of Soft-touch Thermoplastic Elastomers

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Abstract

This Guide presents guidance for good practice in the psychological assessment and physical characterisation of soft touch materials: It covers

- The establishment of sensory evaluation groups
- Determination of a common vocabulary for psychological assessment
- Determination of psychologically relevant physical characteristics of soft-touch materials
- Methods for deriving psychophysical relationships
- Predictions of the ‘hardness’ of soft-touch materials using mathematical models (Finite element analysis)

Example results are presented to illustrate the above methods.

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Predicting and Measuring the ‘Feel’ of Soft-touch Thermoplastic Elastomers

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Foreword

This Good Practice Guide outlines a practical approach to assessing the 'feel' of soft touch materials and a methodology for predicting their 'hardness'. In particular it covers:

- Approaches to sensory panel evaluation
- Derivation of an appropriate vocabulary
- Establishment of psychophysical relationships
- Physical characterisation of soft-touch materials
- Modelling the performance of soft-touch materials

Examples are used to illustrate the implementation of these methods.

The information presented in this Guide has been gathered under a DTI funded programme of research *Measurements for Processing and Performance Programme*, via project *MPP7.7: Metrology of Soft Touch Polymers and Elastomers*. This project was carried out by a collaborative group consisting of NPL and City, University of London.

Soft metrology is a multidisciplinary subject that lies at the interface between metrology, materials science and psychology. Being able to identify more objective approaches to assessing human perception of materials is a fundamental goal of soft metrology. The establishment of reliable links between perception of materials and their physical attributes opens up new pathways for product design and approaches to tactile design in a virtual environment.

The Guide contains a description of how to conduct both psychological and physical tests for characterising soft-touch materials and provides examples of how these data can be used to predict the feel of materials.

1 Introduction

‘A soft-touch feeling is difficult to quantify by test methods and is largely subjective’. This statement summarises the problem faced by manufacturers of products where the ‘feel factor’ plays an important role in the customers perception of quality. During the past 8 – 10 years the concept of a soft-touch feel has been applied to plastic mouldings. It is very easy to get lost in the semantics of vocabulary in this area: the term softness is loosely used to describe the physical as well as sensory attributes of materials. Usually the softness of a material is taken to be a measure of compressibility but softness in a sensory sense is much more complicated than this and involves contributions from surface texture, thermal conductivity and friction. Physically soft materials do not necessarily have the most desirable characteristics of soft materials in a sensory sense: compare the feel of a rotting melon with a feather pillow. It is this difference that is the key issue in characterising soft-touch materials in general and in particular soft-touch plastics. The sense of touch is a combination of stimulations derived from direct contact with an objects surface and a more general sensing of movement. Touch, as a sense has received far less attention than vision or hearing as a topic of psychological research. A brief introduction to the psychology of touch may be found in Appendix 1.

This guide describes a robust approach to psychological testing that can be used to evaluate rubber-like soft-touch materials. A link has been established between perceived hardness and physical hardness that can be exploited via finite element modelling to predict the hardness of overmoulded soft-touch materials. This information can be used as a design tool or as a method for screening different soft-touch materials. It should be recognised that this approach has not been widely established and some users may encounter materials that do not behave as expected. Research in this area is continuing.

1.1 What is softness?

The sensation of **softness** can refer to surface softness or bulk softness or some complex combination of the two. **Surface softness** perceived by the fingertips is a measure of the **smoothness** of a surface and is a reflection of the surface profile and friction.

Bulk softness is a measure of the compressibility of a material. It is a complex measure comprising of contributions from basic materials parameters such as tensile, compressive and shear moduli. Materials such as wood can have high values of surface ‘softness’ and minimal bulk softness whereas a feather pillow will have both significant levels of bulk and surface softness. In materials science the term ‘**hardness**’ is used as a measure of bulk softness of

rubbery materials according to the Shore hardness or International Rubber Hardness Degree, (IHRD) scales. For consistency the term ‘hardness’ will be used in the guide to mean ‘bulk softness’.

1.2 What are the desirable characteristics of soft-touch plastics?

The most common class of soft touch materials are the thermoplastic elastomers, copolymers of elastomer and thermoplastic. These materials have a significant benefit over conventional rubbers in that they can be moulded using conventional plastics processing equipment. Typically thermoplastic elastomers are overmoulded over ‘conventional’ plastic skeletons made from, for example, polyethylene or polystyrene. The overmoulded layer has a rubbery feel to it that is much softer than can be achieved by thermoplastics alone.

Soft-touch plastics need to feel comfortable to touch i.e. not clammy or cold and be cosmetically acceptable. They may also need additional properties such as resistance to chemical attack, excellent wear resistance and where appropriate, be approved by regulatory bodies for medical and food applications depending on the application of the product. Good adhesion of the overmoulded layer coupled with high wear and chemical resistance is essential for applications such as paint scrapers and other tools that are likely to be exposed to organic solvents. Excellent adhesion and high wear resistance are necessary for hammer handles and high quality cosmetic finishes are required for toothbrush and hair-brush handles.

2 Using a sensory panel to evaluate materials

Sensory panels are used to measure and interpret human sensory reactions to materials according to their appearance, smell, taste, feel and sound. Sensory analysis includes both qualitative and quantitative measurements. There are published guidelines that provide sufficient information to carry out sensory measurements in an unbiased way. A list of standards in this area may be found in Annex 2.

The sensory panel is created and managed by a **sensory analyst** who is also responsible or interpreting the results provided by the panel members or **sensory assessors**. A sensory assessor is expected to have ‘normal’ primary senses i.e. have the ability to describe product characteristics and be trained in the use of senses. This requires knowledge of the terminology and any scales that are used to describe a materials characteristic, examples of which are shown in Tables 1 and 2 (section 2.3).

2.1 Test conditions

Environmental variables that may have to be controlled include humidity, air temperature and room odour. Ideally the assessors should be in a quiet room and not be in eye contact, i.e. separated by panels. Design guidelines for sensory laboratories can be found in ISO 8589:1988. The sensory analyst needs to ensure that the products being assessed are appropriately labelled and that the assessors are not affected by sensory fatigue – i.e. the desensitising of the senses that occurs during a prolonged series of tests.

The analyst needs to consider whether the test material should be hidden from view or not, this can be an issue if the objects exist in a range of colours or if one is different to the rest. This can be achieved either by blindfolding the subject, or by placing the test object behind a screen or in a container that has an limited access port. Different light sources produce colour casts that can influence the perceived colour of an object. This issue is particularly important when colour matches are required between dissimilar materials.

Where odour detection or taste is important e.g. in the manufacture of cooking implements or children’s toys, sensory assessors should avoid extraneous or potentially disturbing factors such as eating spicy food or smoking prior to a test, and the use of scents. It is also important to ensure that the assessors are healthy and in a ‘stable’ condition. Obviously colds and flu-like symptoms will impair smell, taste and potentially hearing, but there are more subtle factors that affect sensory perception such as tiredness, stomach upsets, psychological stress and pregnancy.

2.2 Sensory tests

Sensory tests are either objective or descriptive. Objective or discriminative tests rely on identifying differences between sets of samples according to the following test procedures:

- **Triangle test:** the assessor is asked to identify the odd one out in a set of three samples, two of which are identical.
- **Paired comparison test:** assessors are asked to compare samples presented in pairs on the basis of one or more defined characteristics.
- **Duo-trio test:** the assessors are presented with a control followed by two samples, one of which is identical to the control sample. The assessor is asked to identify the sample which is either the same as, or different from, the control.
- **Ranking test:** the assessors are asked to rank a series of samples in order of intensity or degree of a particular characteristic.

In **subjective or descriptive** tests assessors are required to describe in words the characteristics of a material. For **intensity measurements** assessors are asked to use numbers *or* words to describe the intensity of a perceived attribute, *or* asked for their reactions to the attribute i.e. degree of softness. Whereas the assessors are asked to detect and describe their sensory assessment of a sample, rating the intensity of each attribute in **profile or quantitative descriptive analyses**.

The performance of a sensory panel can be assessed by carrying out occasional replicate analyses of samples that are introduced on a random basis. This provides some measure of the repeatability of the measurements.

2.3 How to conduct a vocabulary elicitation study

Establishing a common list of terms that can be used to describe people's perception of a material is key to the success of any psychological tests programme. Factors including sex, age, the ethnicity of the participants – to accommodate cultural differences in perception and the native language of the participants need to be considered when recruiting assessors for the study. It is also advisable to obtain references from the assessors in their own language so that any limitations in vocabulary due to using a second or third language do not skew the results.

The statistical reliability of the data for any given group of individuals obviously increases with an increasing number of participants. A minimum of at least six participants in any one group is recommended. The tests should be conducted on a one-to-one basis to avoid any 'group' influences with the samples presented in a random order. The participants are asked

to describe the materials that they assess and these adjectives are logged. The analyst must also decide whether the assessors should be allowed to handle the samples freely or whether the samples should be mounted to ensure consistency in handling.

Some consideration should also be given regarding the cleanliness of the samples and the strategy used to clean or not clean the assessors' hands. Washing the samples with detergent prior to drying, wiping with an alcohol impregnated cloth or a dry lint free cloth are all viable approaches, depending on the type and finish of the test materials. It is generally good practice to ask the assessors to wash their hands using soap and water prior to taking part in the test. However, arguments can also be made for not following this procedure as material in contact with un-washed hands is more representative of reality.

2.3.1 Analysis of the results

The vocabulary elicitation study will produce a range of descriptive terms of which a significant proportion will be synonyms. These data can be analysed in terms of their frequency of use. This approach will highlight terms that have the most common usage, Table 1. These data although of interest have limited value since some of the words used in common parlance may be synonyms or near synonyms of others. A card sorting study can be used to remove words with the same or similar meanings. This approach uses a much smaller panel of subjects to group the words produced in the vocabulary elicitation study into smaller subgroups, Table 2. The participants are not given any guidance as to how many subject headings should be used or any other information that could bias their decision making process.

The vocabulary elicitation study should be analysed to determine whether sex, ethnicity or age are significant factors or not, the results of this analysis will subsequently impact on the make up of the sensory evaluation panels used to identify potential psychophysical relationships. In the absence of any statistically significant correlations a mixed age, sex and ethnicity panel can be used for subsequent tests.

The groupings of words for each participant are recorded and used to produce a data matrix that lists the number of times each word is grouped with every other word. This matrix can be analysed using a non-parametric cluster analysis using a statistical package, for example, SPSS, (www.spss.com). The output of this analysis is a series of clusters that are categorised into '...tighter and tighter clusters of maximum similarity, and separations into disparate clusters with maximum dissimilarity' (Snodgrass et al, 1985). Cluster analysis reveals the average groupings of elements, i.e. groupings of words, across a number of participants and shows the strength of these groupings, Figure 1. Each cluster can be examined to extract a title or key word together with a description of it.

Table 1: Seven most frequently used words from the vocabulary elicitation study

Word	Number of participants
Smooth	62
Sticky	54
Hard	48
Rubbery	46
Soft	38
Gripping	32
Slippery	26

Very close associations between specific words in a cluster are also displayed in the dendrogram (for example, *spongy* and *squashy* or *elastic* and *flexible*). The card sorting exercise and subsequent cluster analysis is an approach to identifying clear groupings of the words into distinct clusters. The following clusters were obtained from sensory panel analysis of a series of thermoplastic elastomers (Petrie et al, 2004):

- “feminine” which describes the basic perceptual sensations related to simple touching of surfaces.
- “pleasant”, describes the psychological connotations and emotional reactions to the plastics materials.
- “elastic”, describes some of the basic physical characteristics of plastics.
- “masculine” which includes words associated with masculinity. This can be further subdivided into two components concerned with functionality and solidity of the material.
- “uncomfortable”, words that relate to discomfort such as yucky and sticky.
- “Robust”, words that are associated with the concept of strength.
- “malleable”, words that are associated with material compliance

It is important that sensory panels assess test items using a common, restricted list of terms that are associated with feel as shown in Table 2. These terms are used in subjective tests to assess materials. It is possible to generate quantitative data using these descriptors by assigning values to them over the range of an agreed scale.

Table 2: Results of the cluster analysis for a card sorting study used in the vocabulary elicitation study.

Cluster Title	Example words in the cluster	Comments and associations
Feminine	Silky Soft Slimy Slippery Shiny Smooth Synthetic	Words associated with the feminine gender type and direct sensational perception.
Pleasant	Comfortable Comforting Erotic Sensual Sweetie Giving	Words associated with a general psychological and emotional reaction to the material
Elastic	Elastic Flexible Pliable Rubbery	Words that describe elasticity properties, reflecting the flexibility of the material.
Masculine (hard)	Functional Gripping Cold Dry Blu-tak Heavy Light Firm Hard Matt	Words associated with the masculine gender type and are material related. This cluster could also be further divided into two separate clusters; • <i>Functionality</i>: Functional, Gripping, Cold, Dry, Blu-tak • <i>Solidity</i>: Heavy, Light, Firm, Hard, Matt
Uncomfortable	Sticky Tacky Unpleasant Yucky Warm Wet	Words that are generally associated with negative emotions.
Robust	Resistant Robust Masterful Thick Unyielding	Words that have a strong association with the concept of strength.
Malleable	Spongy Squashy Squeezable Stretchy	Words that are associated with the compliance of the materials

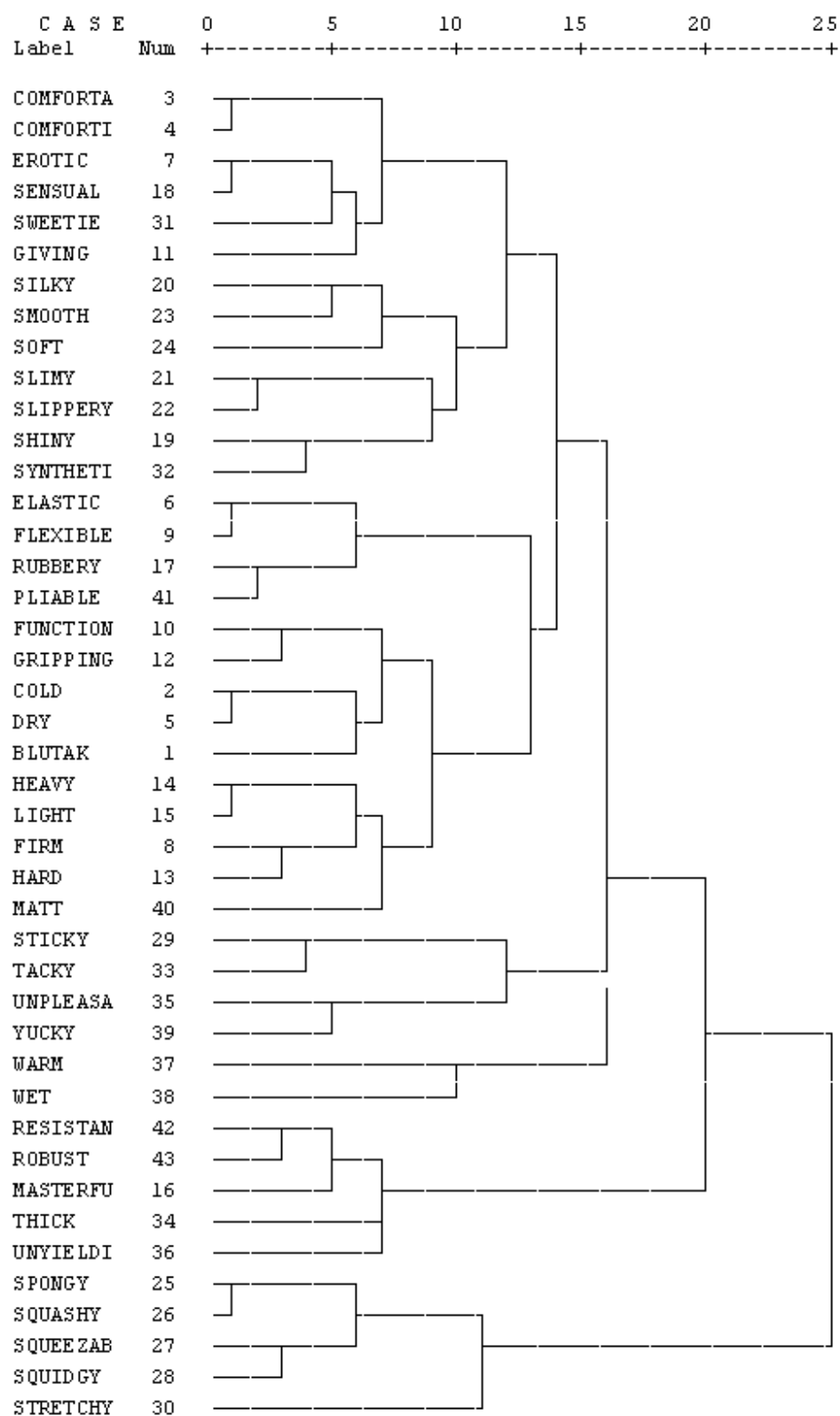


Figure 1: Dendrogram of clusters

2.3.2 Other approaches to psychological assessment of materials

Satzger, 1990, has attempted to correlate physical measurements made on soft-touch paints with subjective assessments made by apparently untrained assessors. The assessments were made with respect to a PVC covered 'standard' and graded as being 'too hard', 'too soft' or 'comparably soft'. An envelope of the range of desirable friction coefficients and hardness (the measured physical parameters) was obtained by identifying samples with comparable softness to PVC in a plot of hardness versus coefficient of friction as shown in Figure 2. This concept assumes that any coating/substrate combination that falls within the envelope will have a 'desirable' feel. The concept is attractive although Satzger has not reported whether or not it works in practice.

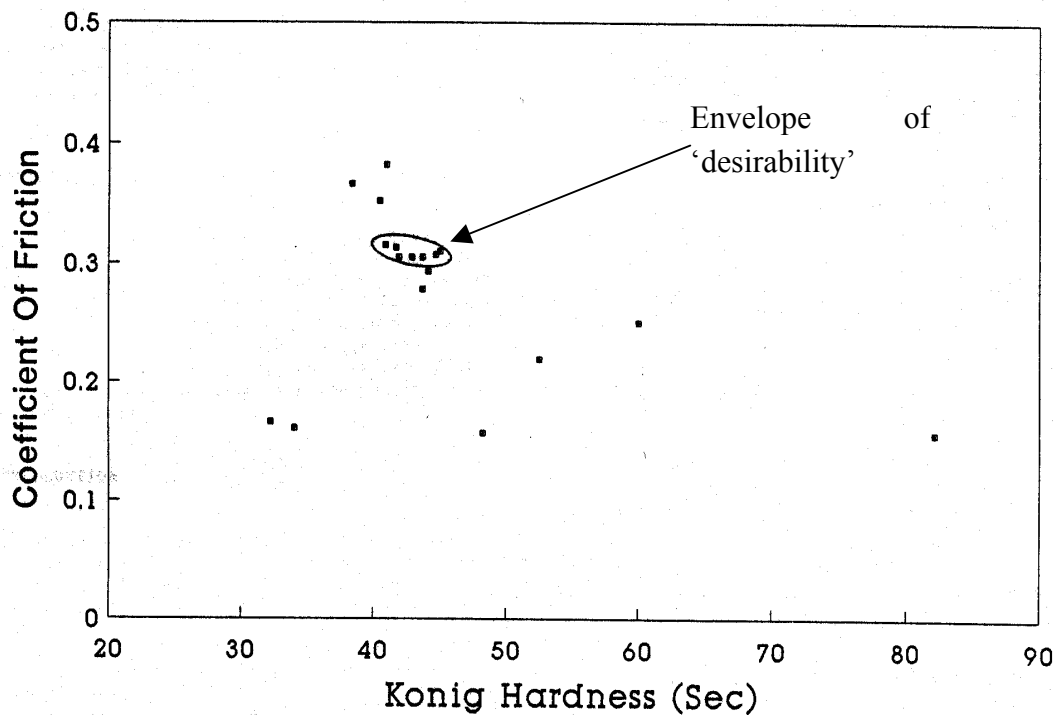


Figure 2: An envelope of desirable properties can be defined in a plot of hardness versus the coefficient of friction to screen different materials for a particular application (redrawn from Satzger 1990).

Shear et al, 1997, has also published a list of descriptors that can be used to assess foams, Table 3. The value of this work is in providing a set of terms that can be easily associated with experiences that the assessors will have or can easily obtain. A similar approach could be used to assess the feel of soft-touch rubbery materials.

**Table 3: Sensory descriptions used to characterise foams
(after Shears et al 1997).**

Test Method	Description	Comment	Example
Passing a finger over the sample	Damp	A moist or wet sensation	Damp sponge
	Rough	Uneven surface	Concrete or stone
	Noisy	Produces sound as finger moves over surface	Expanded polystyrene Drinking cup
	Friction	Resistance to finger movement	Eraser
	Sticky	Tacky surface feel	Glue
Gradual compression of the block by the palm of the hand	Elastic	Rapid recovery of foam after deformation	Spring
	Soft	Easily deforms due to pressure	Freshly baked bread
	Constant Pressure	Deforms but offers resistance	Ripe soft cheese
	Malleable	Easily deformed, slow to recover	Modelling clay

2.4 Psychophysical assessment of softness

In planning the object evaluation study the sensory analyst needs to consider whether the object geometry is a potentially significant factor or not, a choice that depends on the intended application of the material. However, Petrie et al, 2004 have shown that both object geometry and material thickness are not significant factors influencing perception. Most everyday objects that we touch can be grouped into three categories: flat surfaces, curved surfaces and cylindrical surfaces that may invoke different sensory responses depending on their detailed geometry. Significantly increasing the diameter of a small cylindrical object such as a pencil will result in different populations and combinations of cutaneous and kinaesthetic receptors being utilised¹.

Objects for test panel evaluation can be manufactured in a range of geometries if required as shown in Figures 3, 4 and 5 by attaching the material to a mandrel. The success of this

¹ These sensory receptors are discussed in more detail in Section 6.2.

approach relies on having materials that are flexible enough to form over the mandrel. Care should be taken to ensure that any joins are as smooth as possible.

2.5 Procedure

An active touch paradigm whereby the participant is allowed to move their finger(s) across/into the sample provides both cutaneous and kinesthetic information for the participant. Quantifiable comparisons of the different materials can be obtained using the magnitude estimate method approach²

A pilot study should be carried out to ensure instructions are clear and that touch procedures can be reliably reproduced. The following procedure for evaluating softness can be used to illustrate a test methodology.

- For flat samples participants are asked to press the index finger of their dominant hand into the sample in a downward fashion (Figure 3). Samples should be placed on the same rigid surface for all trials to create an equal level of resistance.



Figure 3: Procedure to assess the softness of a flat sample

² Psychophysical investigations attempt to link our psychological reactions with the physical measurable properties and are used to establish quantifiable relationships between physical stimuli and perception based on uni-dimensional scaling (magnitude estimation) or cluster analysis (Snodgrass et al, 1985).



Figure 4: Procedure to assess the softness of a cylindrical sample

- For cylindrical samples, participants are asked to grasp the sample with their dominant hand and apply moderate force with their fingers and thumb (Figure 4).
- For curved samples, participants are asked to straddle the sample using their second finger and thumb of their dominant hand whilst applying a downward pressure in conjunction with the index finger (Figure 5).



Figure 5: Procedure to assess the softness of a curved sample

Assessors are first presented with a sample with a mid-range hardness. This sample acts as a point of reference and is assigned an arbitrary value, for example, 10. Participants are then presented with each of the other samples in the set and asked to assign an intensity value to each relative to the reference sample. For example, if an assessor feels a given sample is twice as soft as the reference then they would assign a softness value of 5, if on the other hand they thought it was half as soft they would assign it a value of 20. The assessors are permitted to feel the reference sample within any given set of samples at any point during the evaluation process.

Assessors should be encouraged to give their first reaction to the sample. Limiting the number of amount of times that the evaluators touch each sample to around three reduces loss of fingertip sensitivity and overtiring. Finger bowls of water can be provided to help participants revive their fingers and remove any residue if required. Practice and fatigue effects, can be eliminated by presenting the samples in a random order.

2.6 Psychophysical linkages between reality and perception

Identifying potential relationships between a physical attribute of a soft-touch materials and the perception of that property can be identified using the Analysis of Variance (ANOVA). Perceived values are assumed to be the dependent variable and factors such as sample type, thickness, geometry and details of the participants are assumed to be independent variables. Figure 6 shows a very clear relationship between the perception of softness and the physical hardness of the samples that is not affected by other factors investigated such as the thickness of the sample, the shape of the surface presented, or the sex of the participant.

It appears that statistically significant correlations between physical and perceived qualities can be modeled using a simple power law relationship, following that described by Steven's (Stevens, 1975), i.e.

$$ME = a.SI^b \quad (1)$$

where ME is the estimated magnitude of a stimulus and its physical magnitude is SI. The parameters a and b refer to a scaling coefficient and an exponent respectively. For the data shown in Figure 6 the exponent 0.9, a value that compares well with published data for squeezing rubber (0.8) and palm pressure – applying a static load to the skin (1.1) (Stevens, 1975). Such well defined linkages can be used to, for example, predict the 'feel' of a material from a known physically measured hardness.

Similar procedures can be devised to check out friction, warmth, smoothness etc.

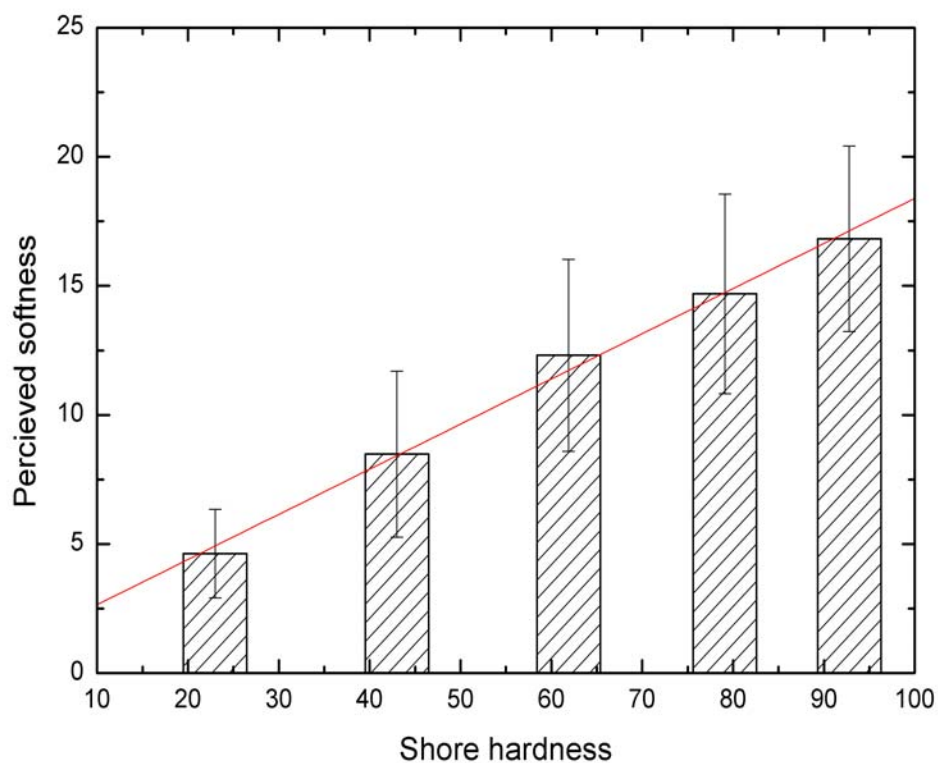


Figure 6: Relationship between physical hardness (Shore A hardness) and perceived softness (Raw Magnitude Estimate, ME) for all sample types

3 Physical characterisation of soft-touch materials

The physical properties that primarily influence our perception of a material based on touch alone include:

- Surface profile
- Surface friction
- Thermal diffusivity, a combination of thermal conductivity and heat capacity
- Mechanical properties – a measure of the materials response to prodding, squeezing and shearing/stroking

Table 4 shows how these physical qualities relate to our perception of a material. A brief outline of the techniques that can be used to measure these properties are given below.

Table 4: Perception and physical characteristics

Perception	Descriptive words	Dominant physical characteristic
Feel - warmth	Comfortable Sensual Comforting Erotic	Calculation of the thermal diffusivity (3.1) requires measures of: • Thermal conductivity (3.1.1) • Heat capacity (3.1.2) • Density (3.1.3)
Surface related perception	Shiny Slippy Gripping Matt Tacky Sticky	• Surface topography (3.2) can be assessed by measuring its gloss (3.4) or profile (3.2.1) or by direct viewing (3.3) • Skin-material friction coefficient (3.5)
Mechanical aspects	Stretchy Resistant Firm Hard Squeezable Squashy	• Shore hardness (3.6) • Tensile modulus (3.7) • Shear modulus (3.7.1)

3.1 Thermal properties

Some materials feel cool to touch whilst others feel warm. This perception depends, in part, on the thermal properties of the material i.e. its temperature, thermal conductivity and heat capacity. At room temperature materials with large heat capacities and thermal conductivities such as copper will initially feel cool to touch since they will rapidly wick heat away from the skin. Materials with opposite properties e.g. expanded polystyrene foam will feel warm to the touch. The thermal diffusivity, α of a material is a measure of the rate at which thermal energy is dissipated and is defined as

$$\alpha = \frac{\lambda}{\rho * C_p} \quad (2)$$

where λ is the thermal conductivity, ρ is the density and C_p the heat capacity of the material. Obviously if these are known then the thermal diffusivity can be determined.

3.1.1 Measurement of thermal conductivity

The basis of any thermal conductivity measurement is to measure the rate at which heat passes through a sample. The guarded hot plate apparatus is seen as the gold standard for this type of measurement and is described in ASTM C 177 and ISO 8302. The apparatus consist of a hot plate sandwiched between two cold plates. A flat sample of the same material is located between the central hot plate and one of the cold plates. A second sample of the same material of different thickness is located between the opposite side of the hot plate and the second cold plate. Platinum sensors monitor the heat flux through the sample from the central heated plate to the cold plates from which the thermal conductivity can be obtained.

An alternative approach which is utilises the same principle is shown in Figure 7. The sample (diameter 9.8 mm, length approximately 50 mm) is sealed within a heated chamber. The measurement cycle consists of inserting a probe that contains both a heating element and a thermocouple into the sample which is maintained at constant temperature (Dawson et al, 2005). A known voltage is then applied to the heater element in the probe for a short period of time and the change in sample temperature is recorded by the probes thermocouple.

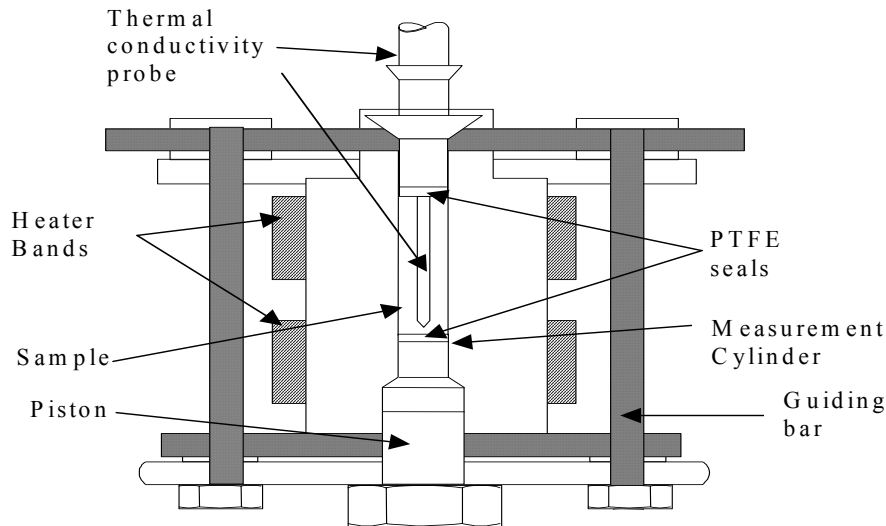


Figure 7. A Schematic of Thermal conductivity apparatus

The thermal conductivity of a material can be obtained from a plot of sample temperature versus $\ln(\text{time})$. The temperature rise ΔT from temperature T_1 to T_2 produced within the probe, over the time interval from t_1 to t_2 is given by

$$\Delta T = T_1 - T_2 = \frac{Q}{4\pi\lambda} \ln\left(\frac{t_1}{t_2}\right) \cdot B \quad (3)$$

Where Q is the input heat and λ , the thermal conductivity (Oemke and Wiegmann, 1994).

Measure thermal conductivity over the range at which the material will be used.

3.1.2 Determination of specific heat capacity

Measurement of the specific heat capacity of a material can be obtained from a calorimeter. In a differential scanning calorimeter, DSC a sample of known weight is placed in a holder and the amount of energy, provided by an electrical heater, required to increase the temperature of the sample per degree is measured (ISO 11357-1). The test is carried out at a constant heating rate during which the heater power is continuously and automatically adjusted to compensate for heat absorbed or evolved by the sample to ensure that the sample holder temperature is identical to that of the reference holder. The energy input to the electrical heater is measured. The DSC is calibrated with a certified reference material (sapphire). Sealed aluminum pans are used to contain the samples during measurement. The sample size is 10 mg – 15 mg. Specific heat capacity measurements are typically made over the range –at which the material will be used at using a heating rate of approximately 10 °C/min.

Based on the DSC principle (ISO 11357-1) and the definition of the specific heat capacity it can be shown that the specific heat of the specimen, c_p^{sp} can be obtained using equation 4

$$c_p^{sp} = c_p^{cal} \cdot \frac{m^{cal} (P_{specimen\ run} - P_{blank\ run})}{m^{sp} (P_{calibration\ run} - P_{blank\ run})} \quad (4)$$

where m^{sp} and m^{cal} are the masses of the specimen and sapphire calibrant respectively, P is the heat flow rate (dQ/dt) for tests on the empty pan ($P_{blank\ run}$) and pans containing the specimen ($P_{specimen\ run}$) and calibrant ($P_{calibration\ run}$), and C_p^{cal} is the specific heat of the sapphire calibrant. Further details of the derivation of this function and the experimental procedure are to be found in ISO 11357-1 and ISO 11357-4.

3.1.3 Measurement of density

The density of a block of material can be simply determined by measuring the dimensions of strips used for mechanical testing and weighing them. The accuracy of such measurements improves with increasing the size of a well-defined shaped sample.

3.2 Methods for determining surface profile

The profile or texture of a surface represents the deviations from a nominal surface that forms a three-dimensional surface. Such deviations can be repetitive or random. Typically surfaces are characterised using the two-dimensional (2-D) profile formed by the intersection of a plane perpendicular to it. The orientation of this perpendicular plane is chosen to maximise the contours of the profile. Surface textures can also be captured and analysed using commercially available software in 3-D. However the methods utilized are not yet supported by published standards. A description of the terminology and methods for analyzing 2-D data can be found in Leach, 2001.

A variety of methods including atomic force microscopes, laser profilometers and white light interferometers can be used to measure surface profiles on length scales ranging from nanometres to micrometres (Tomlins et al, 2005). These data can be described in terms of roughness parameters that quantify, for example, the deviation of the profile from the mean, or record the magnitude of the highest peak and deepest valley. Care should be taken to ensure that the length scale i.e. micrometres, over which data are required is that which directly relates to touch; there is little merit in measuring on a length scale that exceeds to the sensitivity envelope of the cutaneous or kinaesthetic transducers.

3.2.1 Laser profilometry

Laser profilometers are used to map surface profiles in both 2 and 3 dimensions. Such devices work by maintaining a point focus during a surface scan. This is achieved by moving the objective up or down which provides a direct measure of the surface profile. This type of non-contacting technique is well suited to measuring the profile of soft, easily deformed, surfaces. The resolution of laser profilometers depends on the sensor used and typically ranges from 1 μm to 10 μm , noting that any increase in scan resolution will result in longer scan times, a factor that increases significantly for area scans.

The technique does have its limitations. The instrument relies on the sample having a certain amount of reflectivity and although this is quite low at approximately 4%, it can pose problems for transparent or semi-transparent materials. A second practical difficulty is encountered in samples that have features with sharp drop-offs or undercuts due to loss of focus as a result of the often limited working range of laser profilers and lack of light penetration respectively. Absorption of light by pigments can also add to the practical challenges of this type of measurement.

Laser profilometers can be used to scan relatively large areas of sample ranging from a few mm^2 to cm^2 . The in-plane resolution for the data depends on the sampling frequency: any gain in resolution has to be offset against an increase in measurement time. Typical conditions for sampling a 5 mm^2 area of sample may be a sampling frequency of 100 points per millimetre and a scan speed of 50 points per second. The resulting profile is then filtered and analysed using commercial software such as that provided by Mountains Universal® software. Further details of filtering and sampling lengths can be found in ref leach.

3.3 Visual inspection of the surface

Optical microscopy should be used to inspect the surface of soft-touch materials. The information that this simple method provides can be used to assess the homogeneity of the surface and to detect the presence of, for example, foreign bodies – soft materials are prone to picking up contaminants from their surroundings i.e. paper fibres and dust which alters both their feel and skin-surface friction coefficients.

If required surfaces can be investigated in more detail using scanning electron microscopy, (SEM). Non-conductive rubber-like materials require a conductive coating that can be sputtered on to the sample. This coating prevents electric charge accumulation. Details of sputtering, sample preparation and usage can be found in Gedde, 1995. The disadvantage of

this approach is that the area imaged is very small and hence may not be representative of the sample as a whole.

3.4 Measurement of surface gloss

Changes in the texture of a surface affect its appearance by reducing the mirror or specular relectivity measured at fixed and identical angles of incidence and reflection, typically 20°, 60° and 85°. Gloss is usually expressed as a percentage, and defined as the ratio of the luminous flux reflected from an object in the specular direction for a specified source and receptor angle to the luminous flux reflected from a highly polished black glass reference. The refractive index of the black glass standard is 1.567 in the specular direction and the angle used for measurements is 60° if the procedure described in ASTM standards D2457-3 and D523-89 is followed.

Specular gloss is usually used as a comparative measure of surface properties since it usually varies with surface smoothness and flatness. The amount of light reflected from a surface also depends on the concentration and type of pigments that may be present that limits the usefulness of gloss measurements in comparing differently coloured materials. Gloss measurements provide a rapid means for assessing surface consistency and will provide a semi-quantitative measure of changes in surface appearance due to wear or contamination.

3.5 Measurement of surface friction

Friction between the skin and a material is a significant factor influencing our perception of the ‘feel’ of an object. Artefacts can feel, for example, dry, grippy, greasy, smooth, rough or slippery depending on the frictional force that develops during handling. The magnitude of this frictional force depends on contributions from adhesion and deformation. Adhesion between a probe, i.e. a finger, and test surface will increase the frictional load. Deformation of either the probe or test material will have the same effect. Friction can be quantified by defining a friction coefficient as

$$Cf = \frac{Ff}{Fv} \quad (5)$$

where Ff is the in-plane frictional force and Fv the vertical force as shown in Figure 8.

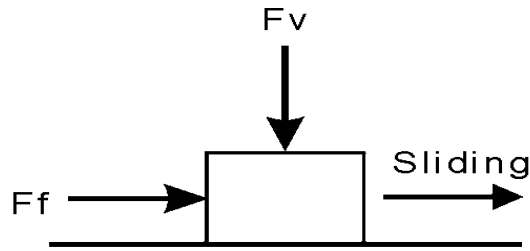


Figure 8: The frictional force, F_f is equivalent to the friction coefficient, C_f multiplied by the applied vertical force, F_v .

Two different friction coefficients can be defined. The static friction coefficient is defined as the peak in friction when the two surfaces just start moving over one another (Figure 9). Before this occurs, the friction trace moves up a diagonal line as the force stored elastically in the contact increases. The samples start moving relatively when the force generated by deformation of the “spring” of the contact increases to exceed the static frictional force. The dynamic friction is defined as the friction coefficient that occurs when the two surfaces are moving freely over one another. Large differences in friction coefficient or high contact compliance can lead to the phenomenon of stick-slip where a repeated sequence of the two samples stopping and moving occurs (Figure 9b).

Several approaches to measuring skin-material interactions are available: most instruments constrain the ‘skin’ i.e. the subjects arm or finger and move the material over it in a controlled way or vice versa (e.g. Sivamani et al). The rationale behind this approach is to define a protocol that can be repeatedly used on a number of volunteers over extended periods of time. However, in reality we have freedom to explore the feel of an object as we wish. This can be accommodated in the friction rig design shown in Figure 10. The system uses strain gauged flexure elements to detect in-plane forces in both X and Y and the applied normal force in Z, (Gee et al, 2005a and b). Testpieces up to 150 mm by 150 mm can be attached to the test-bed platen. Stroking the sample at any speed with one or more fingertips produces directionally dependent frictional forces and a normal force that can be used to monitor the position of the finger. These data are captured and analysed to produce values for the normal load, frictional load, friction coefficient, X-Y position and X and Y speed.

Typical data obtained using this type of instrument is shown in Figure 11. Measurements can be made on materials that have not been previously tested, or the effect of repeated handling can also be explored. Comparisons with traditionally used hardened steel and rubber balls can be used as control data.

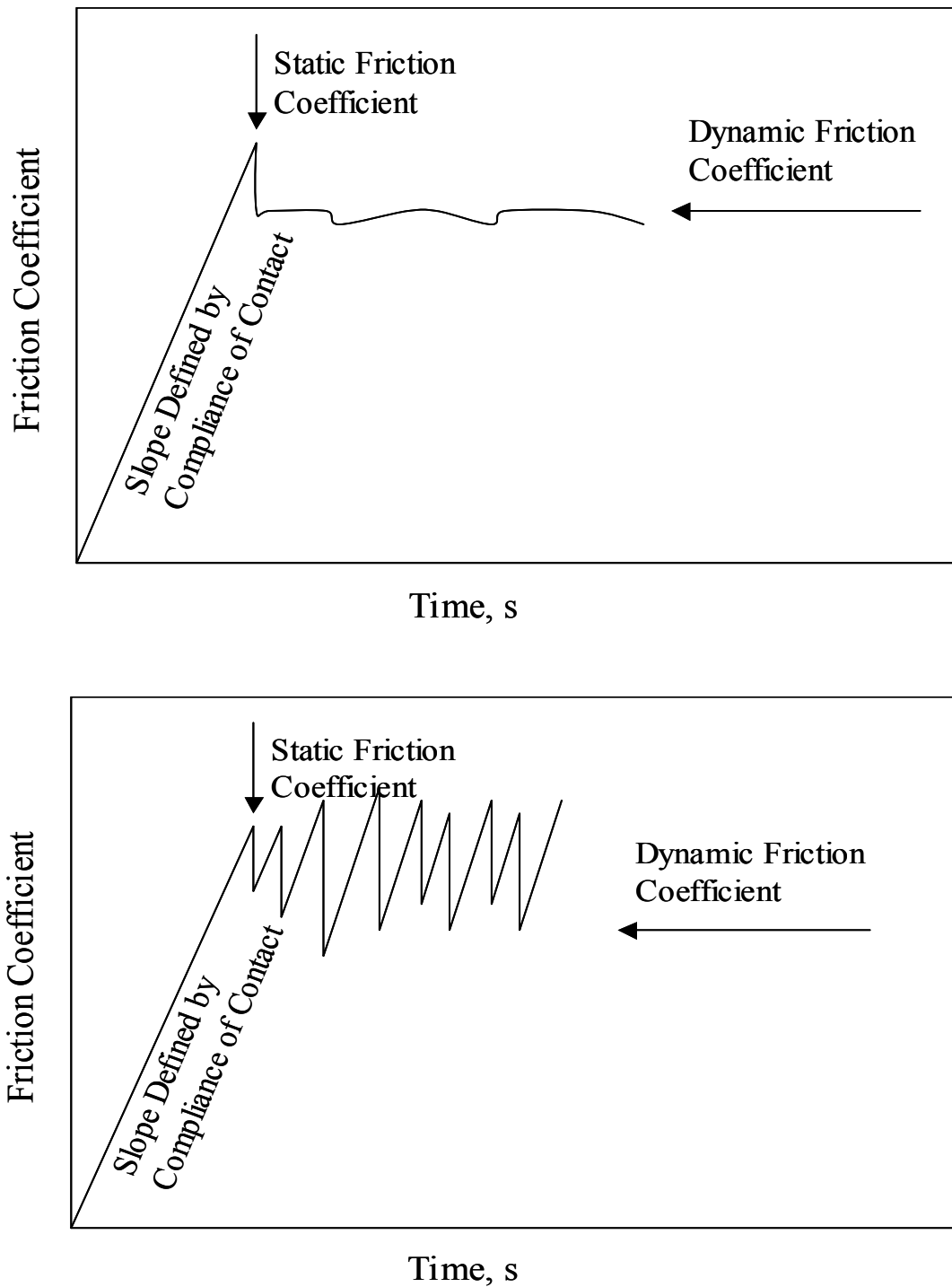


Figure 9. Schematic diagram of friction behaviour, a) static friction coefficient larger than dynamic friction coefficient, b) where large difference in static and dynamic friction coefficient or high compliance contact leads to stick-slip behaviour

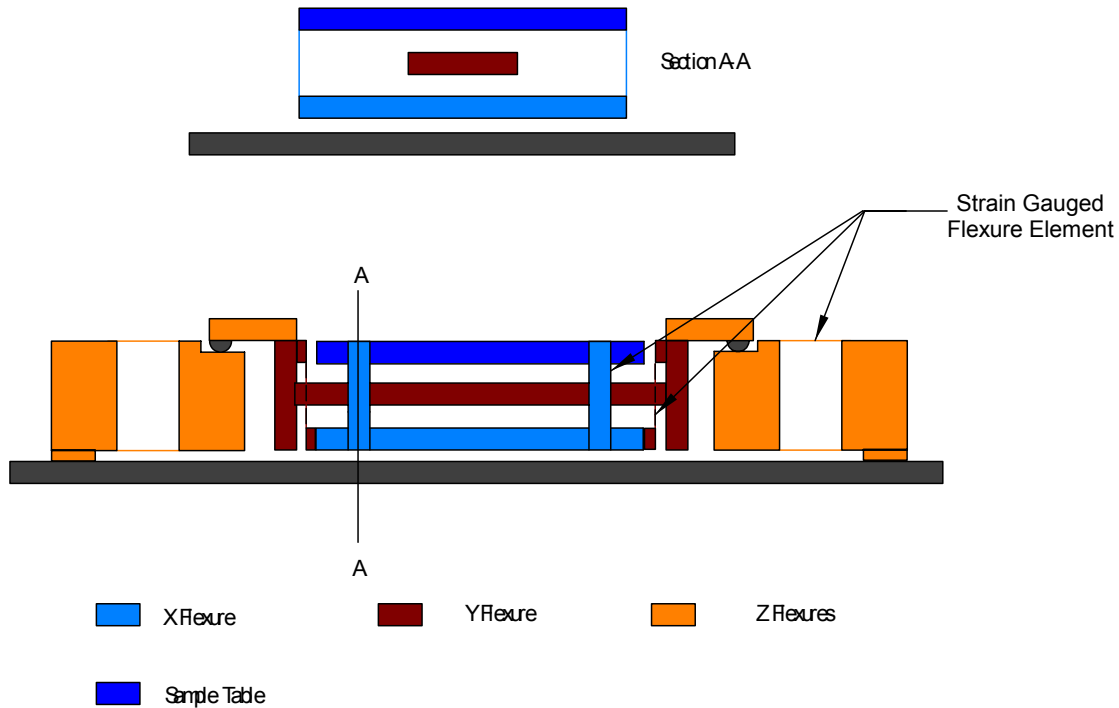


Figure 10. Schematic diagram of soft metrology friction test system

3.6 Shore hardness

Soft-touch materials are typically assessed by compression during prodding, stroking or gripping. This approach is similar to measuring the indentation of a probe to produce a value for the ‘hardness’ using the Shore (or Durometer) or International Rubber Hardness Degrees (IHRD) scale. During the test, a small round end indenter with known dimensions is pushed into the material under a controlled load for a specified time period. The time delay is to allow for the strain relaxation behaviour of the material. The standard test, ASTM D2240-04, specifies a minimum thickness for the material and areas where measurements cannot be made. This eliminates any contributions to the measurement from the underlying substrate from edge effects. At the end of the time period, the remaining depth of the indenter is measured and a value from 0 (full protrusion) to 100 (no protrusion) is quoted.

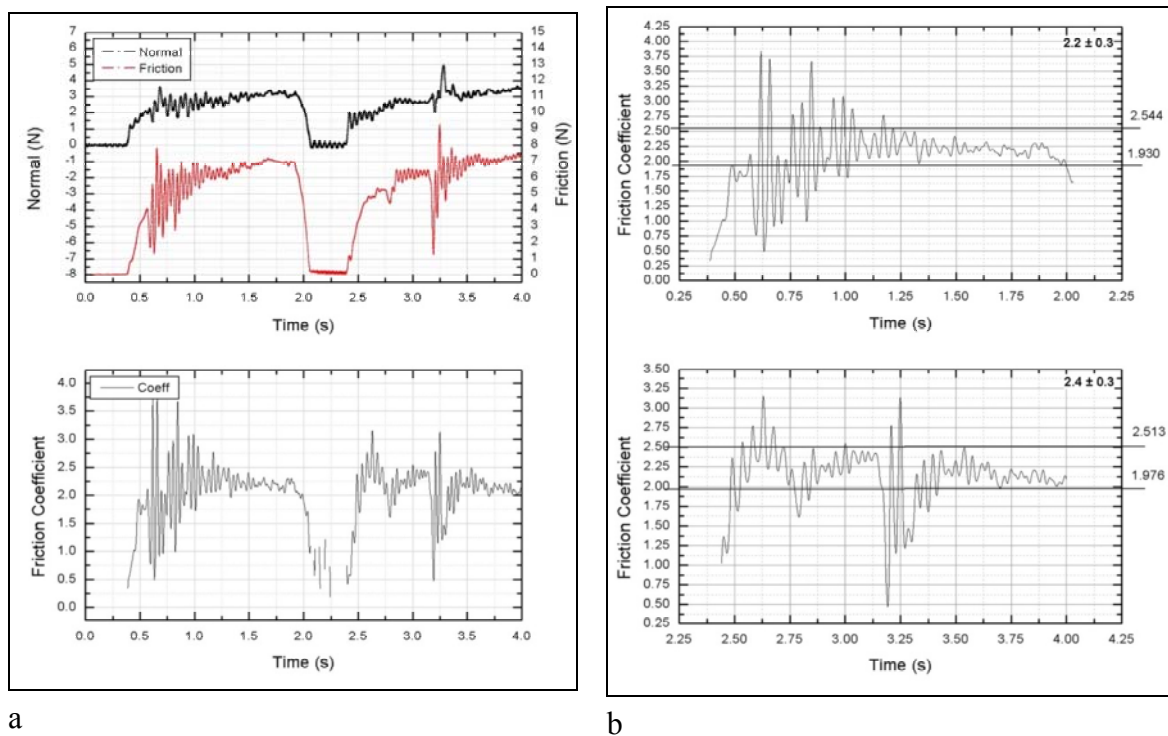


Figure 11. A typical plot of skin-surface friction coefficient for a soft touch thermoplastic elastomer (material F002). All data: (a) Upper and lower bounds of the friction coefficient (b).

The indenter geometry shown for the commonly used Shore A scale, Figure 12, is selected on the basis of the nominal hardness of the material and the results are then quoted with respect to the scale used. Materials that register more than 90 on the A scale should be measured on the Shore D scale and softer materials below 20 Shore A need to be assessed using the Shore O scale. Although this type of measurement is low cost and rapid to make, the data generated are *not* regarded as a material property due to the complex stress state that arises during indentation. Shore hardness data are therefore used for comparative purposes.

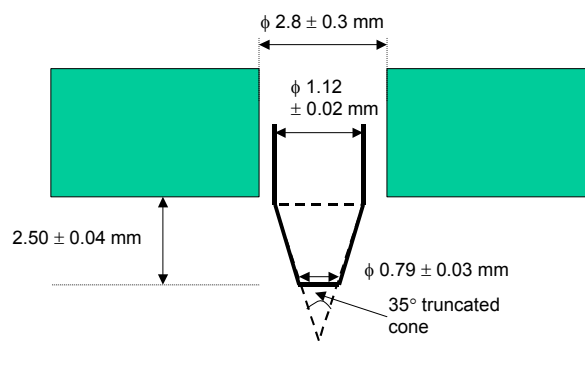


Figure 12. A schematic representation of the indenter used to measure hardness on the Shore A scale (redrawn from ASTM D 2240-04)

3.7 Mechanical characterisation –

3.7.1 Tensile properties

The act of squeezing or stroking rubber essentially involves applying a shear stress to the material. Experimentally the very small strains that are produced by these shear stresses are difficult to measure, hence it is common practice to measure properties in tension and convert them to shear using Poisson's ratio.

A test under a constant deformation rate is commonly used to determine the mechanical properties of elastic materials. A plot of stress against strain is a straight line at small strains where the behaviour is linear. With viscoelastic materials, the stress/strain plot is a curve, even when behaviour is linear viscoelastic. The shape of the curve varies with strain rate. The gradient of a stress/strain curve therefore depends both upon strain and strain rate. These phenomena are a direct consequence of the variation of deformation behaviour with time under load, and consequently, this method has limited value for determining properties such as modulus.

Rubbers are often loaded with fillers, such as carbon black, to improve their mechanical properties or to reduce material costs. The presence of carbon particles increases properties such as $E(t)$ and E' in equations (6) and (7) and makes them strain dependent. Doubling the strain in a measurement of this type of material does not lead to a doubling of stress, and the deformation behaviour is therefore referred to as non-linear. In the case of carbon particle reinforcement, the non-linear behaviour is significant at small strains (in the region of 1% and less) and is attributed to a breakdown of the particle structure with increasing strain level. The breakdown is recoverable, but the recovery is not immediate and can take hours depending on the type of carbon black and the maximum strain sustained in a test.

The mechanical properties of viscoelastic materials are commonly determined using stress relaxation or creep experiments. In a stress relaxation test, a constant strain ϵ_s is applied and the time varying load is measured to determine the time dependent stress $\sigma(t)$. If a uniaxial tensile strain is applied, then a tensile stress relaxation function can be determined using the equation

$$E(t) = \sigma(t)/\epsilon_s \quad (6)$$

The quantity $E(t)$ can be considered as a time-dependent Young's modulus. This behaviour is linear viscoelastic if $E(t)$ is independent of the magnitude of ϵ_s . It should be noted that due to the Poisson effect the cross-sectional area of a tensile sample will decrease with increasing strain and the true stress should be calculated using the current area rather than the original

area. For small strains (<5%) the cross-sectional area can be considered invariant with strain, and the engineering stress determined using the actual cross-section and true stresses are approximately equal.

Measurements of stress $\sigma(t)$ with time under strain at selected strains ϵ_s should start at the lowest strain and then move progressively to higher values. A time interval between tests of at least the duration of the previous test should be used to allow the specimen to recover from the applied strain before beginning the next measurement. Values for stress relaxation modulus are derived using equation (6) and are plotted against time under the applied strain.

3.7.2 Dynamic mechanical properties

Mechanical properties can also be determined using dynamic mechanical tests in which a sinusoidal, time-varying strain is applied and the time-varying stress is measured. For a viscoelastic material, the stress and strain waveforms are out of phase. If the stress and strain waveforms are tensile and have amplitudes σ_o and ϵ_o respectively, and the phase difference is δ , then a dynamic tensile modulus E' can be determined using the equation

$$E' = \frac{\sigma_o \cos \delta}{\epsilon_o} \quad (7)$$

This dynamic modulus (also referred to as storage modulus) depends on the measurement frequency and can be correlated with the stress relaxation modulus in equation (6) through expressions that relate the frequency to an effective time in a stress relaxation test.

To facilitate correlations with relaxation data, the same specimen dimensions and interval clamp length should be used. Dynamic mechanical tests are commonly used to determine the variation of the dynamic modulus with temperature and explore the dependence of modulus on the dynamic strain amplitude.

4 Prediction of feel

Ideally predictions of the feel of a material should be based on sound psychophysical relationships using models that are able to reliably predict the behaviour of a material under different loading regimes, overmoulding thickness' and areas. This approach can be costly in developing appropriate models and collecting sufficient and appropriate experimental data. An alternative approach, illustrated in case study 1, is to develop a semi-qualitative model.

4.1 Case Study 1: Predicting the feel of soft-touch paints

Kawaza et al (2000) have attempted to quantify the feel of soft-touch paints using a combination of sensory and physical measurements. Sensory evaluation was carried out by ranking samples in terms of their:

- Moist or dry feel
- Smooth or rough feel
- Warm or cool feel
- Soft or hard feel

Using either comparisons of pairs or by ranking a number of samples. These data were then scored i.e. the warmest feeling surface was awarded 3 points and the coolest -3 and so on. A multiple regression approach was used to find the coefficients in the function:

$$S1 = a(\text{moist-dry feel}) + b(\text{Smooth or rough feel}) + c(\text{Warm or cool feel}) + d(\text{Soft or hard feel})$$

Where S1 is the softness of the paint. The values of the regression analysis indicate the relative importance of different aspects of feel and suggest that the smoothness of the surface plays only a minor role in surface softness. The dominant factors are 'soft-hard' followed by 'moist-dry', i.e. the softest perceived surface would feel moist and soft to touch.

4.2 Case Study 2: Shore hardness Pprediction

A reliable psychophysical relationship established between perception and a physical aspect of the material can be usefully exploited through modeling to predict the feel of a material in a virtual environment. Figure 6 shows an excellent correlation between the perceived hardness and physical hardness of a range of thermoplastic elastomers. This behaviour can be modeled using finite element methods providing that the behaviour of the material can be

mathematically modeled. The latter requires an understanding of the material to obtain appropriate data and to generate the functions required. The key steps of this process are shown in Figure 13.

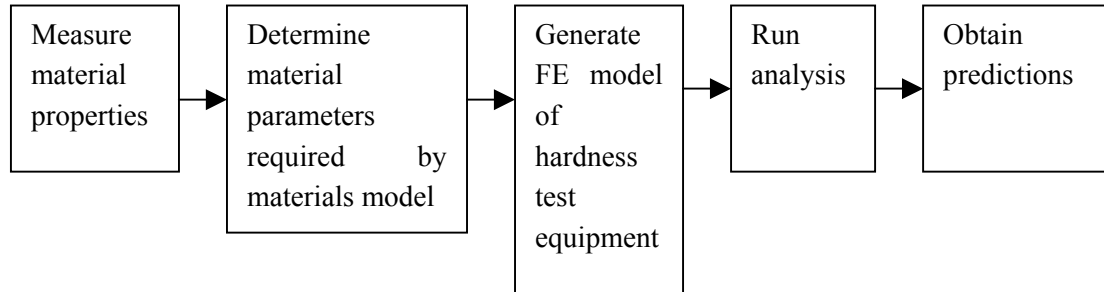


Figure 13: The basic steps that lead to modelling the perceived hardness of rubber.

Finite element analysis (FEA) can be used to model the geometry of the Shore A hardness test. A preprocessor is used to create the geometry, mesh and to define the constraints of the test. The geometry modeled is shown in Figure 12.

4.2.1 Geometry and Mmesh

Having established a model and obtained the necessary parameters the geometry of the system needs to be meshed. The geometry of the elements and their dimensions needs to be able to reliably capture the displacements that occur in those regions where the sample is being deformed. Constraints need to be applied which mimic the test procedure i.e. for the hardness test and the boundaries of the material (slave) and indenter (master) surfaces need to be defined. The software also needs to be recognize that the outer sleeve will not penetrate into the rubber after initial contact.

The symmetry of the test equipment can be exploited to produce a half model of the geometry that can be meshed using axisymmetric elements. The specimen can be assumed to be cylindrical. A typical half symmetry mesh is shown in Figure 14. The steel casing and indenter are modelled as elastic elements, and the hypoelastic model was chosen for the rubber specimen. Contact surfaces are defined between the casing and the specimen, and the indenter and the specimen. A displacement when applied to the casing, moves it into contact with the specimen. The outputs selected are the spring relative displacement and spring elastic force.

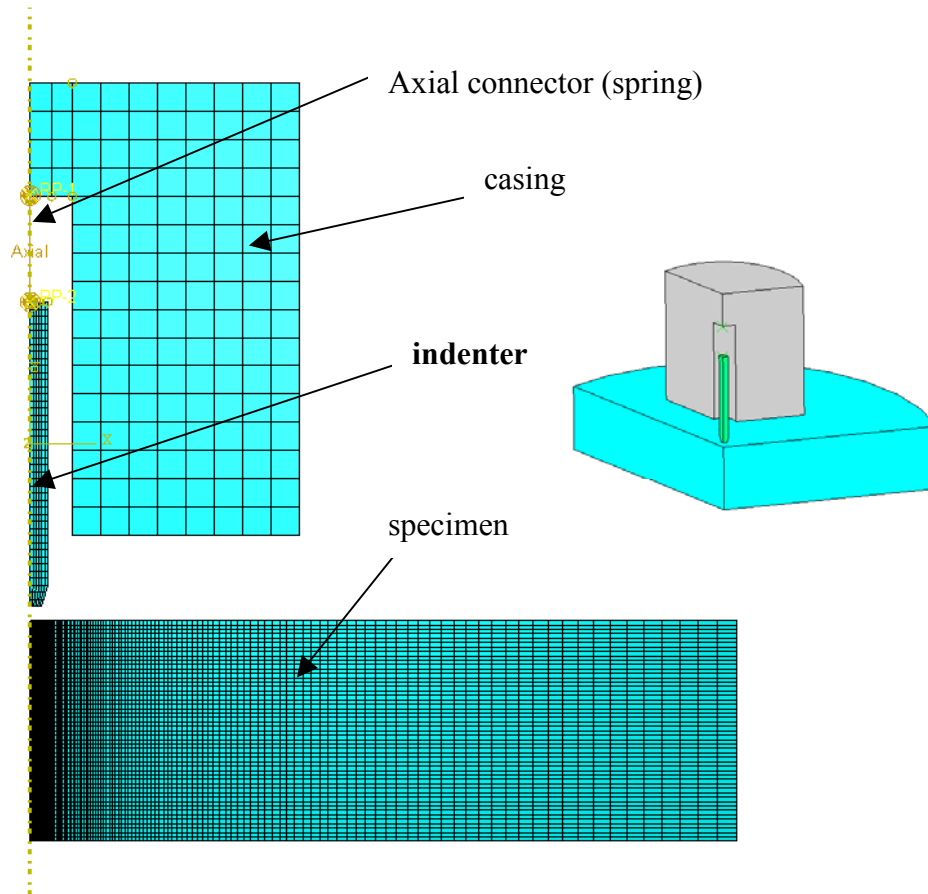


Figure 14. Axisymmetric finite element mesh of the Shore A hardness indenter.

4.2.2 Analysis

The FE software can then be run to predict the indenter displacement from which the Shore hardness can be determined. It is important to validate this process as the model develops and is run in a virtual environment which can be done by calculating experimentally verifiable values for Shore hardness. A further check should be made to ensure that the model predicts a value of 100 Shore A is obtained if steel is substituted for the rubber.

The following points should be considered:

- Is the mesh suitably detailed to fully capture all displacements?
- Ensure that the calculated strains are within the range of the models predictions and well supported by experimental data.
- Consider the influence of friction between the indenter and the rubber sample which may reduce the calculated deformation of the rubber, leading to a higher Shore index prediction.
- Note that the materials model will be material specific and may well be specific to a particular grade of material. This will be especially true for rubbery materials.

4.2.3 Results

Figure 15 shows typical results of a finite element simulation of the Shore hardness test. The calculated penetration depth of the probe is used to calculate the equivalent Shore hardness that can be confirmed by experimental measurement, Figure 16. The results can be used to predict the Shore hardness and hence the perceived hardness of overmoulded TPE's of any thickness and geometry.

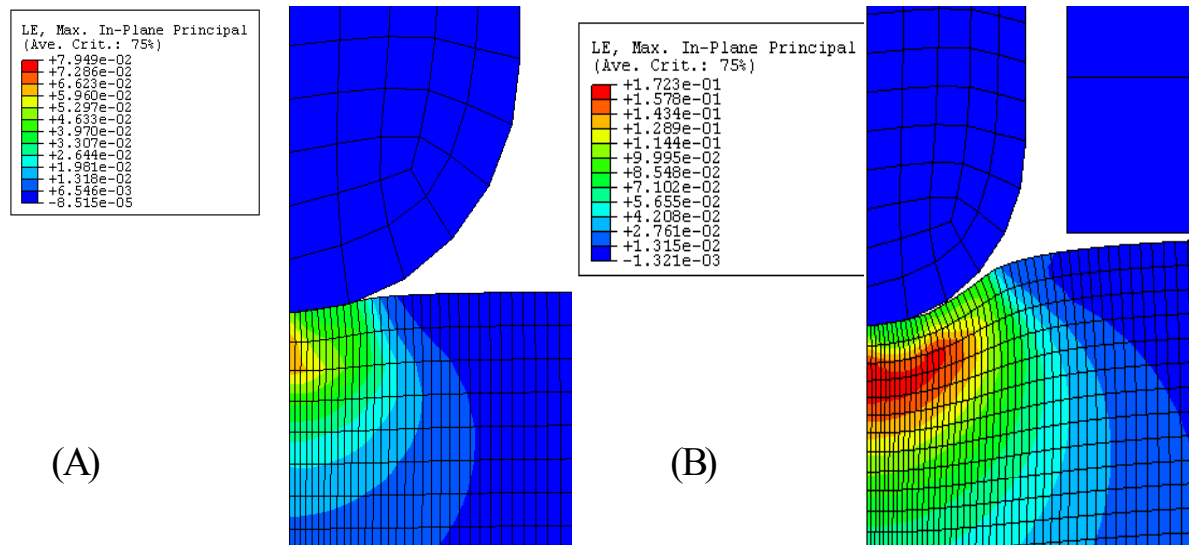


Figure 15. The development of strain with the TPE due to penetration of the indenter, B is at a later time than A.

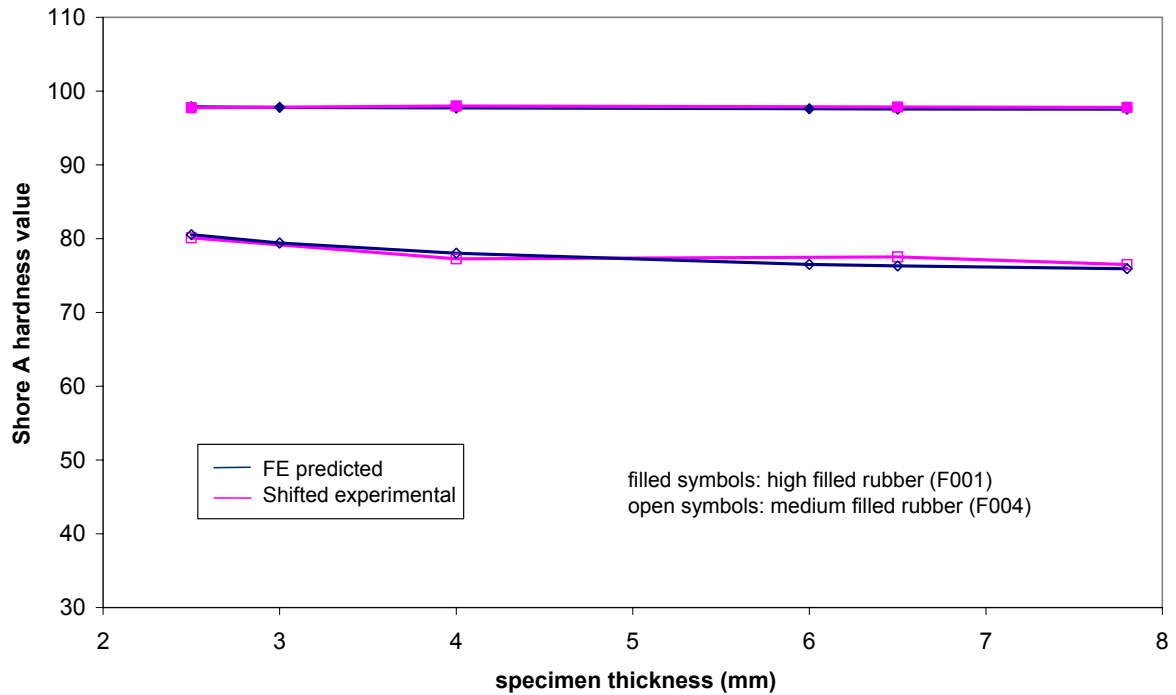


Figure 16. A comparison of experimental Shore hardness data with that predicted for materials of different thickness.

Further information on this process is available in Crocker et al, 2005.

5 REFERENCES

Allard, F. (2004) Lecture 4: Direct scaling. [Online]. Available:

ASTM C177. Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus.

ASTM D 2240-97: Standard test method for rubber property – Durometer hardness BS 903: Part A57:1997 (ISO 7619:1997) Physical testing of rubber - part A57. determination of indentation hardness by means of pocket hardness meters

ASTM D2240-04 Standard Test Method for Rubber Property—Durometer Hardness

ASTM D2467-03. Standard Test Method for Specular Gloss or Plastic Films and Solid Plastics.

ASTM D523-89. Standard Test Method for Specular Gloss (1999).

Bicchi, A., De Rossi, D. and Sciling. P. (2000). Haptic discrimination of softness in teleoperation: The role of the contact area spread rate. *IEEE Transactions on Robotics and Automation*, 16(5), 496-504.

Bafnec M.; Juma M.; Toman J.; Juriová J.; Ku ma A. Thermal diffusivity of rubber compounds *Plastics, Rubber and Composites: Macromolecular Engineering*, Volume 28, Number 10, October 1999, pp. 482-486(5)

Colwill, M. J., Warren, S., Workman, C., Jones, K., Robins, T., Rait, J., De Pennington, A., and Childs, T. (2003). Affective Design (Kansei Engineering) in Japan. Leeds: University of Leeds Media Services.

Craig, J.C. and Rollman, G.B. (1999). Somesthesia. *Annual Review of Psychology*, 50, 305-331.

Crocker L E, Dean G D and Tomlins P E, A Method for Predicting the Perceived Hardness of Soft-Touch Elastomeric Coatings and Over-Mouldings, NPL Report MPR-035, November 2005.

Dawson, A., Rides M. and Nottay, J. The Effect of Pressure on the Thermal Conductivity of Polymer Melts, NPL Report, in preparation.

Gedde U, Polymer Physics, Kluwer Academic Publishing, 1995.

Gee M G, Tomlins P.E., Calver A., Darling R.H., Rides M., A new friction measurement system for the frictional component of touch, 15th International Conference on Wear of Materials, San Diego, USA, 24-28 April 2005

Gee M.G., Tomlins P.E., Calver A., Darling R.H. and Rides M.; A New Friction Measurement System For Soft Tribology Wear 259(2005) pp1437-1442.

Goldstein, E. B. (1996). *Sensation and perception*. 4th Edition. Pacific Grove, CA.: Brooks/Cole.

H Petrie, N King and P Tomlins. Investigations into Sensation of “Softness” and Perception of the Tactile Properties of “Soft Touch” Thermoplastic Elastomers, DEPC MPR017, December 2004.

http://affect.media.mit.edu/AC_research/recognizing.html [15 July 2004]

<http://www.ahs.uwaterloo.ca/~kin356/lecture4.pdf> [12 July 2004]

ISO 8302. ISO International Standard: Thermal Insulation - Determination of Steady-State Thermal Resistance and Related Thermal Insulation - Determination of Steady-State Thermal Resistance and Related Properties - Guarded-Hot-Plate Apparatus.

ISO 11357-1:1997. Plastics -- Differential scanning calorimetry (DSC) -- Part 1: General principles

ISO 8589:1988 Sensory analysis -- General guidance for the design of test rooms

ISO/FDIS 11357-4 Plastics -- Differential scanning calorimetry (DSC) -- Part 4: Determination of specific heat capacity

Jansson, G., Billberger, K., Petrie, H., Colwell, C., Kornbrot, D., Fanger, J., Konig, H., Hardwick, A. and Furner, S. (1999). Haptic virtual environments for blind people: Exploratory experiments with two devices. *The International Journal of Virtual Reality*, 4(1), 10-20.

Johansson, R. S. and Westling, G. (1990). Tactile Afferent Signals in Control of Precision Grip. In M. Jeannerod (Ed.), *Attention and Performance*. Mahwah, NJ.: Lawrence Erlbaum and Associates.

Katz, D. (1925/1989). *Der aufbau der tastwelt* (The World of Touch). Translated by L.

Klatzky, R. L. and Lederman, S. J. (2002). Touch. In A.F. Healy and R.W. Proctor (Eds.). *Experimental Psychology. Vol 4 of Handbook of Psychology*. New York. John Wiley and Sons.

L E Crocker, G D Dean and P E Tomlins, A Method for Predicting the Perceived Hardness of Soft-Touch Elastomeric Coatings and Over-Mouldings, DEPC MPR035, November 2005.

Labview. A configuration-based route to programming package produced by National Instruments

LaMotte, R. H. (2000). Softness discrimination with a tool. *The Journal of Neurophysiology*. **83(4)**, 1777-1786

Leach, R. The Measurement of Surface texture using Stylus Instruments, National Physical Laboratory Measurement Good Practice Guide No. 37, 2001.

Lederman. S. J. (1974). Tactile roughness of grooved surfaces: The touching process and effects of micro- and macro-surface Structure. *Perception and Psychophysics*, **16**, 385-395.

MIT Media Laboratory . (2004). Research on Affective Pattern Recognition and Modelling.

Mountains Universal software. Micro Photonics Inc. Irvine, California, USA

Oemke F., Wiegmann T, “Measuring Thermal Conductivity Under High Pressures”, 2240/ ANTEC ’94

P E Tomlins, M Rides, A Dawson, M Gee, G Dean, C Hobbs, C Allen, S Gnaniyah, A Calver and R Darling Physical Characterisation of Soft-Touch Polymers, DEPC MPR025, July 2005

P Tomlins and S Kingdon. On the Measurement of ‘Softness’ in ‘Soft’ Touch Plastics and Other Materials, NPL Report MATC (118), September 2002.

Petrie, H., Penn, P. R., Kornbrot, D., Furner, S. and Hardwick. A. (2000). Haptic virtual environments for blind people: Further explorations with the Phantom device. *Proceedings of the 3rd International Conference on Disability: Virtual Reality and Associated Technologies*. Alghero, Sardinia, Italy.

Presence Research. (2004).Psychophysical Measures. Available: <http://www.presence-research.org/Psychophysical.html> [10 July 2004]

Satzger D.H. Characterization of ‘soft-feel’ coatings for automotive interiors, Polymers, Laminations and Coatings conference, Boston, USA, Sept 1990, pp 515-521

Shear, J., Bastin, B. and Banner, C., Sensory Analysis: A new method for determining the feeling and comfort characteristics of flexible polyurethane foams, Polyurethanes World Congress, '97, 1997, p75.

Sivamani, R.K., Wu G., Gitis N.V. and Maibach H.I., Tribological testing of skin products: gender, age, and ethnicity on the volar forearm, Skin Research and Technology, 9,1–7, 2003.

Snodgrass, J. G., Levy-Berger, G. and Haydon, M. (1985). *Human experimental psychology*. Oxford. Oxford University Press.

Snodgrass, J.G., Levy-Berger, G., and Haydon, M. Human Experimental Psychology. Oxford University Press, 1985

Srinivasan, A, and LaMotte, R. H. (1995). Tactual discrimination of softness. *Journal of Neurophysiology*. **73(1)**, 88-101.

Srinivasan, A., and LaMotte, R. H. (1996). Tactual discrimination of softness: Abilities and mechanisms. In O. Frazen, R. Johansson and L. Terenius (Eds.), *Information Processing in the Somatosensory System*. Basel: Birkhauser Verlag.

Stevens, J.C, and Choo, K. K. (1996). Spatial acuity of the body surface over the lifespan. *Somatosensory and Motor Research*, **13**, 153-166.

Stevens, J.C. and Patterson, M. Q. (1995). Dimensions of spatial acuity in the touch sense: Changes over a lifespan. *Somatosensory and Motor Research*, **12**, 29-47.

Stevens, S. S. (1975). *Psychophysics: Introduction to its perceptual, neural and social prospects*. New York: John Wiley & Sons.

Tomlins, P.E., Leach, R., Vadgama, P.V., Mikhlovsky, S. and James, S. On the Topographical Characterisation of Biomaterial Surfaces, Chapter 25 in Surfaces and Interfaces for Biomaterials, Edited by P Vadgama, Woodhead Publishing, 2005.

Wilson, F.R. (1998). *The hand*. New York: Vintage Books.

www.SPSS.com. SPSS inc. is a company specializing in analytical software for scientific and business applications.

6 APPENDIX 1. A Brief introduction to the psychology of touch

6.1 Introduction

The sense of touch is a combination of stimulations derived from direct contact with an objects surface, and a more general sensing of movement. Touch, as a sense has received far less attention than vision or hearing as a topic of psychological research, but it is one that should not be ignored. Human factors research into this topic influences a wide range of industrial designs; from automotive interior components such as steering wheels and gear leavers, watches and computer hardware (Colwill et al., 2003). Research into the development of virtual environments for blind people has also been enhanced by studies into the sense of touch (Petrie et al, 2000).

Studies into the psychology of touch

Studies to measure differences in the compliance of surfaces have been conducted with both human and non-human subjects. Most research since the 1920s (Katz, 1925) focuses on the perceived roughness of surfaces. However, work in recent years has been directed at establishing the perceived compliance, i.e. compressibility, of materials by human touch, most notably by Srinivasan and LaMotte (1995).

Studies into the psychology of touch have to-date applied one of the many established methodologies emerging from the psychophysics discipline. However, research into affective computing conducted at the MIT Media Lab has highlighted alternative methods to analyse the behavioural and physiological expressions of emotion.

‘We are interested in emotional expression through verbal as well as non-verbal means, not just how something is said, but how word choice might reveal an underlying affective state’ (MIT Media Laboratory, 2004)

This concept has been developed further and exploited through the association of adjectival terminology elicitation to translate consumer feelings into design elements (Colwill et al., 2003)

6.2 The Haptic system

The ability of humans to detect the tactile sensation of an object is related to our haptic senses which include the cutaneous or tactile receptors located within the skin which inspire tactile

feedback (Figure A1), and kinesthetic receptors which receive sensory inputs from the body's muscle tendons and joints, thus inspiring force feedback (Figure A2). The human hand and more specifically the fingers are particularly effective at processing spatial information via the skin due to a high density of receptors (Klatzky and Lederman, 2002). Furthermore, neurophysical evidence has identified that the ways in which people grasp, grip and manipulate objects is related to the cutaneous mechanoreceptors present in hairless skin (Johansson & Westling, 1990).

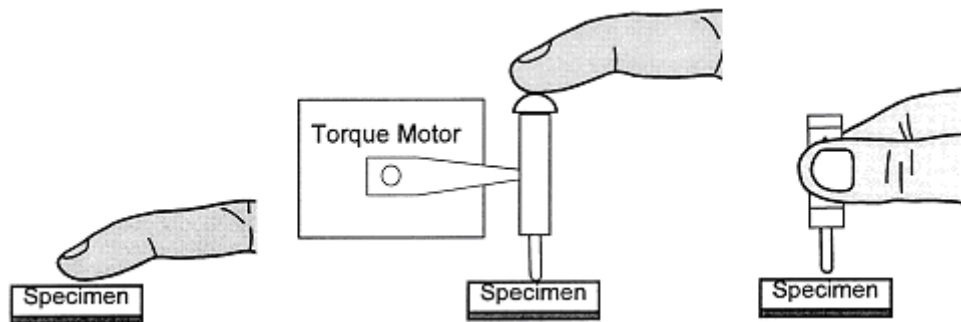


Figure A1: Cutaneous receptors inspire tactile feedback (LaMotte, 2000) Reprinted with permission

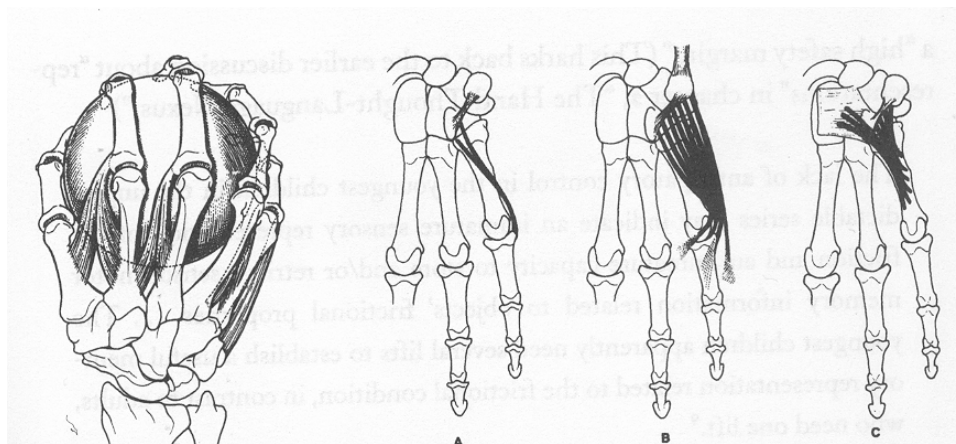


Figure A2: Kinesthetic receptors inspire force feedback (Wilson, 1998) Reprinted with permission

It is widely acknowledged that with age our cutaneous sensitivity decreases due to a loss in the number or sensitivity of receptors. Stevens and Patterson (1995) proposed that an increase in the threshold of the cutaneous mechanoreceptors is approximately 1% per year, between the ages of 20 and 80. More recently Stevens and Choo (1996) evaluated the effects of age upon the threshold of 13 different sites of the body. Their results showed that hands and feet, due to reduced circulation, are the most effected. Thus, affecting our ability to grasp and manipulate objects.

The properties of an object perceived by the haptic system can be separated into two categories; geometric properties concerned with the size and shape of an object and material properties with, for example, texture, compliance and temperature of an object.

6.2.1 Geometric properties

The size and shape of an object determines which aspect of the haptic senses we require to distinguish its geometry. For example, a small object such as a pea has a small radius of curvature, therefore the whole surface can be covered by one finger, thus only requiring the use of cutaneous receptors to establish its shape. Alternatively, more than one finger will be required to analyse the size and shape of a larger object with a small radius of curvature, as a single finger ‘...may not make it discriminable from a flat surface’ (Klatzky and Lederman, 2002). Several fingers provide kinaesthetic information in addition to that generated by several sets of cutaneous receptors, information that is needed to analyse the form of large curved surfaces.

6.2.2 Material properties

Research has shown that surface texture (smoothness) is perceived by running a finger along the surface of an object, identifying the spacing between elements (Klatzky and Lederman, 2002). People generally regard an object, as having a perceivable texture when it has elements that are spaced not more than 3 mm – 4 mm apart. Beyond this limit the object is regarded as being smooth with ‘punctured irregularities’. Additionally, any increase in the height or peak of an element, also leads to a decrease in the perceived texture of the surface. It appears that the kinesthetic receptors have little impact on the perception and triggering of surface texture, which is detected through skin deformation and triggering of cutaneous receptors in the fingertip. Increasing the force of the finger upon the object also increases the perceived magnitude of the smoothness, whereas the speed of motion between finger and surface has very limited effect (Lederman. 1974).

The hardness of an object is subject to its compliance, as perceived by our haptic senses. Bicchi et al (2000) state:

‘It has been firmly established in psychophysical literature that the ability of discriminating softness by touch is intimately related to both kinesthetic and cutaneous tactile information in humans.’

In contrast to the above statement, during Srinivasan and LaMotte’s (1995) work on the tactual discrimination of softness, they conducted active touch experiments in which they

anesthetised the participants' fingers. Thus, the participant was only able to distinguish between soft and hard specimens by using their kinesthetic system. The result was that participants could not even identify the difference between the two extreme ends of the spectrum without the use of their cutaneous system. In contrast, when the experiment was reversed, whereby the participants only had cutaneous information made available to them via a passive touch experiment '...the subjects performed at approximately the same level as under non-anesthetised active touch... Thus tactile information alone is sufficient to discriminate the softness of objects.'

Srinivasan and LaMotte (1996) proposed two separate categories that group objects according to their compliance, and the subsequent proportion of cutaneous versus kinaesthetic receptors required in discriminating them.

- *Deformable objects whose surface is also deformable* e.g. rubber or fruit. Kinesthetic receptors often have little bearing on the judgement of conformance of these objects, cutaneous feedback alone can discriminate the hardness.
- *Deformable objects whose surfaces are rigid* e.g. piano or typewriter keys. Kinesthetic feedback is required in this classification for the object, though rigid on the surface, is compliant when pressed.

6.2.3 Psychophysics

Psychophysical investigations attempt to link our psychological reactions with the physical measurable properties and are used to establish quantifiable relationships between physical stimuli and perception based on uni-dimensional scaling (magnitude estimation) or cluster analysis (Snodgrass et al, 1985).

6.2.4 Established methodologies

The principal route to deriving the relationship between perceived stimulus intensity and one that can be physically measured has not changed significantly since Fechner's pioneering work in the 1860's (Snodgrass et al, 1985). For example, a subject assigns a subjective rating to a stimulus that can be reliably measured. As with all subjective methods, psychophysical measures are susceptible to bias by either the evaluator or the participant or both.

What these methods will measure is heavily dependent on the evaluator's instructions, and on the participant's own interpretation of what they should rate. (Presence-Research, 2004)

The classical methodologies described by Fechner are:

Method of Limit. Regular increases or decreases in intensity. A problem exists in that users may have a tendency to keep responding ‘yes’ in a descending series after the threshold has been reached (error of habituation).

Method of Constant Stimuli. Levels of intensity are repeatedly presented in a random order, the intensity rating that is detected on 50% of trials is awarded the rating of absolute threshold.

Method of Adjustment. Once the stimulus intensity is detectable then an absolute threshold is awarded. Problems exist in the differences in individual perception of stimuli of particular intensities.

Weber introduced another methodology to measure the threshold intensity (Snodgrass et al, 1985)

Signal Detection Theory (SDT). An approach that aims to rectify the susceptibility of Fechner’s methods above to psychological factors (response bias) that may lead to participants believing that they detect a stimulus intensity when they actually do not. There is no *threshold of awareness* as such, but rather a continuum of sensations. According to this theory, the observer will have to establish some criterion for deciding in favour of or against the presence of an external signal. Such a criterion is termed a *response threshold*. It differs from a *stimulus threshold* in that is an arbitrary point along the sensation continuum rather than one fixed by the observer’s sensory system. The observer is as aware of stimuli below the response criterion as of those above it. Because it is an arbitrarily defined point, the subject can easily shift it if the situation demands it.

Magnitude estimation

Magnitude estimation relates the magnitude of physical stimuli to a given number assigned to them (how much of a given sensation a person is experiencing). In magnitude estimation experiments participants are presented with a medium intensity stimulus (the modular) that has an assigned number i.e. 10. The participants are then presented with a series of stimuli that include, and differ, from the mid-range modular intensity, and are asked to assign each of the samples a number relative to the modular. Thus the results are not about absolute accuracy of judgments, but about the relative relationships between judgments of stimuli of different intensities.

The numerical mean of the subjective judgments can then be plotted against the intensity of the stimulus to establish if doubling the actual intensity does lead to a doubling of the

perceived intensity. Stevens displayed that by applying this methodology this is not always the case. For example, Figure A3 displays the perceived magnitude and stimulus intensity for electric shock, line length and brightness. It is apparent that doubling the intensity of light only has a small change on the perceived brightness (response compression), thus it is necessary to increase intensity by up to 9 times to achieve the psychological judgment of double brightness (Goldstein, 1996). In contrast, the doubling of an electric charge is perceived as being extremely more intense (response expansion), and line length is linear.

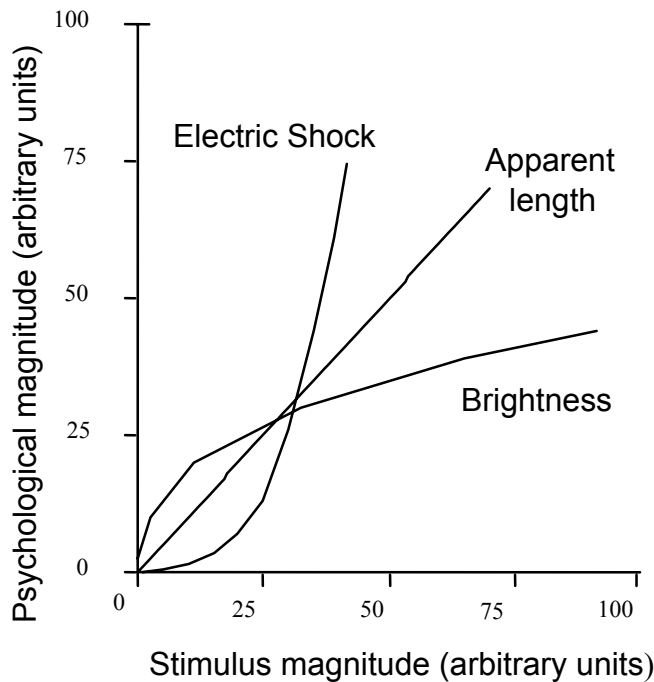


Figure A3: The psychophysical functions for electric shock, apparent length, and brightness (adapted from Stevens, 1975)

The psychological theory underpinning magnitude estimation therefore states that the relationship between perceived psychological intensity, ME is related to the actual physical intensity, SI raised to the power, b , as demonstrated by Stevens power law (Stevens, 1975).

$$ME = a.SI^b \quad (A1)$$

The exponent, b in equation A1 describes the relationship between the intensity of a stimulus and our perception of its magnitude (Jansson et al, 1999). A value below 1.0 means that the physical intensity rises more slowly than physical intensity; values greater than 1.0 mean that the physical intensity rises faster than the increases in physical intensity. Hence, equal ratios of physical intensity and sensation produce a measure of 1.0.

Table A1: Representative exponents of the power functions relating subjective magnitude to stimulus magnitude

Continuum	Measured exponent	Stimulus condition
Visual length	1.0	Projected line
Brightness	0.33	5° target in dark
Electric shock	3.5	Current through fingers
Tactual roughness	1.5	Rubbing emery cloths
Tactual hardness	0.8	Squeezing rubber

Magnitude estimation has received criticism by ‘reflecting more what subjects know about the properties of numbers than the strength of sensations’ (Allard, 2004). In response to this, Stevens developed *cross-modality matching* where by number measures are replaced with non-verbal responses. For example, varying the pressure when squeezing the hand of the evaluator to indicate the tone of a noise, or drawing of a line where the length represents the brightness

Controlled conditions in which participants are asked to perform experiments via *active* or *passive* touch are often applied to magnitude estimation experiments. Active touch represents the most common way humans interact with different materials in real life, enabling kinesthetic and cutaneous feedback. In contrast, passive touch involves the stimuli being presented to the participant, thus only their cutaneous receptors provide feedback. Most research to date has been concentrated around passive touch (Craig and Rollman, 1999).

7 APPENDIX 2: Standards used for sensory analysis

ISO 6658:1985 Sensory analysis -- Methodology -- General guidance

ISO 8586-1:1993 Sensory analysis -- General guidance for the selection, training and monitoring of assessors -- Part 1: Selected assessors

ISO 8586-2:1994 Sensory analysis -- General guidance for the selection, training and monitoring of assessors -- Part 2: Experts

ISO 8587:1988 Sensory analysis -- Methodology -- Ranking

ISO 8588:1987 Sensory analysis -- Methodology -- "A" - "not A" test

ISO 8589:1988 Sensory analysis -- General guidance for the design of test rooms

ISO 10399:1991 Sensory analysis -- Methodology -- Duo-trio test

ISO 11035:1994 Sensory analysis -- Identification and selection of descriptors for establishing a sensory profile by a multidimensional approach

ISO 11036:1994 Sensory analysis -- Methodology -- Texture profile

ISO 11056:1999 Sensory analysis -- Methodology -- Magnitude estimation method

ISO 4120:1983 Sensory analysis -- Methodology -- Triangular test

ISO 5492:1992 Sensory analysis -- Vocabulary

ISO 5495:1983 Sensory analysis -- Methodology -- Paired comparison test

ISO 5496:1992 Sensory analysis -- Methodology -- Initiation and training of assessors in the detection and recognition of odours

ISO 5497:1982 Sensory analysis -- Methodology -- Guidelines for the preparation of samples for which direct sensory analysis is not feasible

