

Selection of materials, manufacturing methods and lubricants for cam mechanisms

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THE PREPARATION OF THIS DATA ITEM

The work on this particular Data Item was monitored and guided by the Mechanisms Committee, which has the following membership:

Chairman	
Dr M.R. Smith	— University of Newcastle-upon-Tyne
Members	
Mr T.H. Davies	— University of Technology, Loughborough
Dr G. Druce	— University of Surrey
Mr A.A. Fogarasy	— Independent
Prof. F. Freudenstein*	— Columbia University, NY, USA
Dr J.N. Hammar	— Design in Motion Ltd, Milton Keynes
Dr K.J. Mashford	— Unilever Research, Bedfordshire
Mr P.M. Nityanandan*	— Gears India (Madras) Private Ltd
Dr A. Samuel*	— University of Melbourne, Victoria, Australia
Prof. D.J. Sanger	— University of Salford
Dr C.W. Stammers	— University of Bath
Prof. J. Volmer*	— Technische Universität, Chemnitz, Germany.

* Corresponding member

The technical work involved in the assessment of the available information and the construction and subsequent development of the Data Item was undertaken by

Mr P.J. Carden	— Senior Engineer, Mechanical Motion and System Dynamics Group
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The person with overall responsibility for the work in this subject area is Mr C.J. Loughton, Head of Mechanical Motion and Systems Dynamics Group.

The Mechanisms Committee, which first met in 1975, is continuing the work that was previously responsibility of the former Gearing and Mechanisms Committee, which first met in November 1964. Like the earlier Committee it has the cooperation of many engineers and scientists in industry, research establishments and universities from whom much assistance and information is being received.

SELECTION OF MATERIALS, MANUFACTURING METHODS AND LUBRICANTS FOR CAM MECHANISMS

CONTENTS

	Page
1. NOTATION AND UNITS	1
2. INTRODUCTION	2
3. FAILURE MODES	4
3.1 Causes of Failure	4
3.2 Pitting	4
3.3 Scuffing	5
3.4 Polishing	5
3.5 Internal Fatigue of Needle-bearing Roller Follower	6
4. DESIGN PROCEDURES	7
4.1 Use of Flowcharts	7
4.2 Specification of Motion, Geometry, Spring and Loads	7
5. MATERIAL SELECTION	10
5.1 General Comments	10
5.2 Initial Choice	10
5.3 Final Choice	12
6. SELECTION OF MANUFACTURING METHODS	13
6.1 General Comments	13
6.2 Profile Generation	13
6.3 Surface Treatments	15
7. LUBRICANT SELECTION	18
7.1 General Comments	18
7.2 Initial Choice	18
8. PERFORMANCE EVALUATION	21
8.1 Estimation of Lubricant Film Thickness	21
8.2 Assessment of Lubricant Film Quality	21
8.3 Estimation of Contact Stress	25
8.4 Assessment of Contact Stress Data	27
8.5 Estimation of Roller Life	30
8.6 Assessment of Roller Life Data	30
8.7 Suggestions for Improving an Acceptable Design	31

9.	DERIVATION AND REFERENCES	33
9.1	Derivation	33
9.2	References	33
10.	EXAMPLES	36
10.1	Initial Design of Cam with Roller Follower	36
10.2	Redesign of an Unsatisfactory Cam Mechanism	40

SELECTION OF MATERIALS, MANUFACTURING METHODS AND LUBRICANTS FOR CAM MECHANISMS

1. NOTATION AND UNITS

The units quoted in the notation are SI but in the text of this Item more familiar units are used occasionally (especially when quantities are inputs or outputs from ESDUComputer programs).

		<i>Units</i>
a	pressure exponent of lubricant viscosity (see Equation (7.1))	m^2/N
E_c	Young's modulus for cam material	N/m^2
E_f	Young's modulus for follower material	N/m^2
E_{eff}	effective modulus (see Data Item 94008, Reference 25)	N/m^2
H_v	Vickers hardness	N/m^2
p	pressure of lubricant	N/m^2
R_{eff}	effective radius of curvature (see Data Item 94008, Reference 25)	m
η_0	dynamic viscosity of lubricant at atmospheric pressure and operating temperature	$\text{N s}/\text{m}^2$
λ	specific film thickness (see Equation (8.1))	—
σ_c	Poisson's ratio for cam material	—
σ_f	Poisson's ratio for follower material	—

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 This page Amendment A

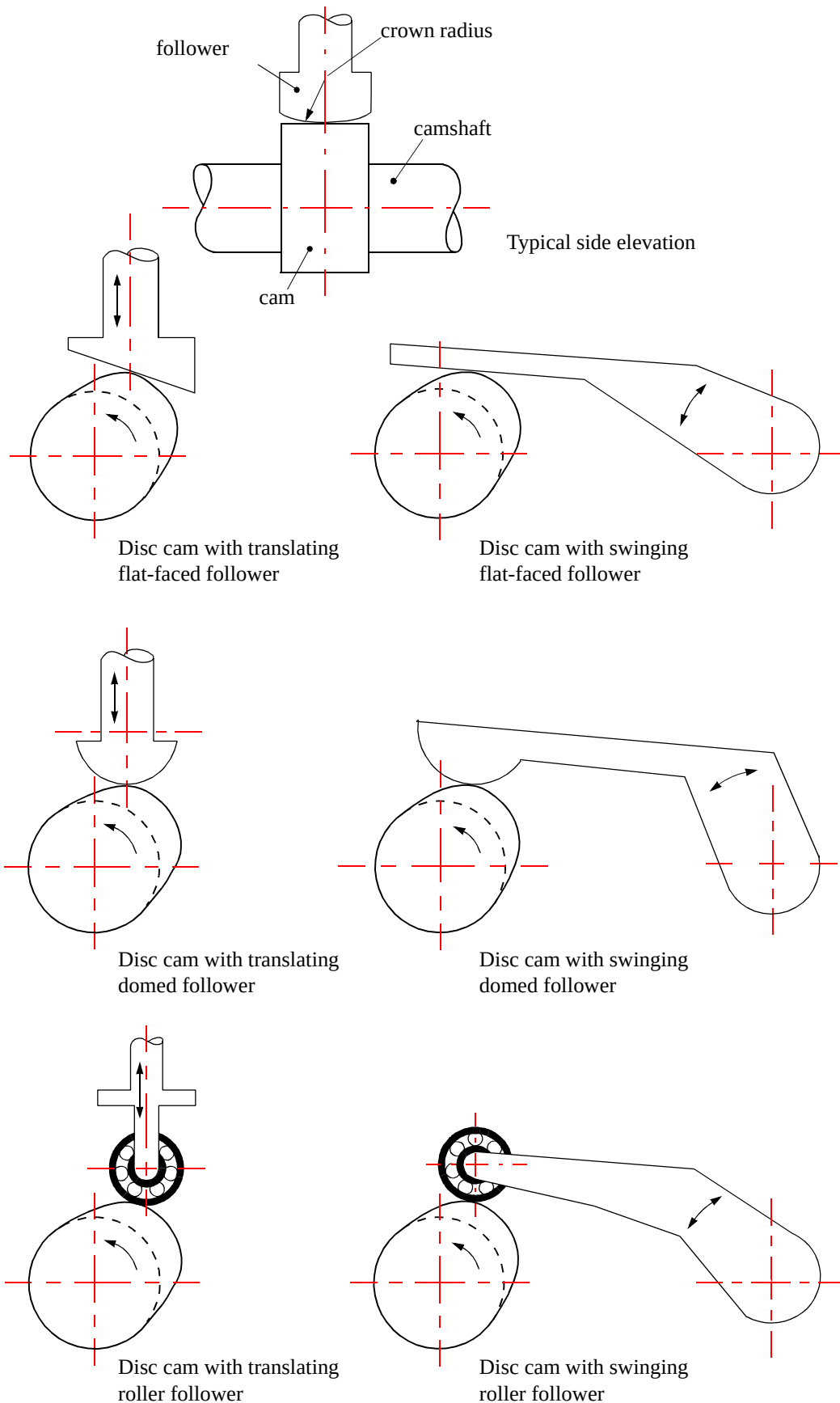
2. INTRODUCTION

The performance of a cam/follower mechanism is critically dependent on the combination of materials used to construct the principal components, the roughness of the contacting surfaces and the properties of the lubricant. Special surface treatments and/or lubricant additives may be necessary to ensure that the mechanism performs its intended function over a specified lifetime.

This Data Item provides guidance on the choice of appropriate materials (see Section 5) and manufacturing methods (see Section 6) including surface finish requirements and surface treatments for a cam and follower of known profile and under known loading conditions. Advice on the selection of a suitable lubricant (see Section 7) is also given. The principal modes by which cam mechanisms fail are identified in Section 3 and procedures for designing against failure by each mode are outlined in Section 4. The design procedures (see flowcharts, Sketches 4.1 and 4.2) are intended for use when the initial layout of a cam and follower, to meet specified motion requirements, is complete. However, it may, in some cases, be necessary to revise the shape or size of the cam and/or the follower in the light of analysis of the contact conditions. The design procedures rely on the evaluation of mechanism performance (see Section 8) using calculation methods and computer software given in Data Items 91026, 93001, 94008 and 94011 (References 20, 23, 25 and 26, respectively).

It must be emphasised that due to the complexity of surface interactions, the lack of reliable data and the uncertainty surrounding operating conditions in many machines, it is not possible to provide unambiguous recommendations for making a successful choice of materials, lubricant, surface treatment and surface finish in all applications. However this Item does provide a rational basis for identifying potential problems at an early stage, choosing between competing designs and exploring strategies for the improvement of existing systems. This Item is most valuable when used in combination with experimentally derived data relating to the performance of materials, treatments and lubricants in an application similar to that under present consideration (see Tallian, Reference 36). Records of the performance of existing mechanisms are extremely valuable.

The procedures in this Item are directly applicable to disc cams with followers of the types shown in Sketch 2.1. However many of the data and much of the design guidance has wider application and may be relevant to the design of other cam/follower systems. Two examples illustrating the use of this Item are given in Section 10.



Sketch 2.1 Disc cams with six commonly used followers

This page Amendment A

3. FAILURE MODES

3.1 Causes of Failure

A cam mechanism “fails” in service if it becomes incapable of fulfilling the function for which it was designed. The prime function of a typical cam is to impart prescribed motion to its follower and so failure is usually defined in terms of a loss of accuracy of the follower motion. This can be caused by:

- (a) fatigue failure of the cam and/or the follower surfaces (known as pitting),
 - (b) excessive wear of the cam and/or the follower surfaces (by scuffing or polishing)
- or
- (c) fatigue failure of the internal parts of a needle-bearing roller follower.

In the following text (Sections 3.2 to 3.5) these processes are described. Cams or followers made from non-metallic materials such as polymers or ceramics may fail by other processes, *e.g.* thermoplastic polymer components may fail if frictional heating raises the temperature of the surface above the softening temperature of the material. These failure modes are not considered explicitly in this Item but Data Item 87007 (Reference 19) contains valuable information on limiting temperatures and rubbing speeds for a range of materials used in the construction of dry rubbing bearings and the computer software associated with Data Item 94008 (Reference 25) can be used to calculate sliding velocity throughout the cycle. Each failure process can be aggravated by misalignment of the cam and follower axes and/or corrosion due to chemical interaction between materials, lubricant and atmosphere. Damage caused by wear particles in the lubricant can also be a significant destructive factor.

3.2 Pitting

Contact between a cam and a follower is usually non-conformal and so the contact area is small and high values of stress are expected. When the cam rotates continuously each point on the surfaces of the cam and the follower is repeatedly loaded and unloaded (with a period inversely proportional to the cam angular velocity) and so failure of the surfaces by fatigue is possible. This is a very widespread cause of failure of cam mechanisms and can be recognised by characteristic irregular “pitting” of the surface (see photograph). The problem begins when microscopic cracks start beneath the surface. The cracks grow under the action of the cyclic stresses until they reach the surface when flakes of material break away. Fatigue cracks can also begin at the surface and this is more likely where there is significant asperity contact (see Section 8.2). Although crack growth is time dependent the appearance of the pits themselves is sudden and the useful life of the system is thereafter short because the pits act as stress concentrations and accelerate further damage.



The surface of a sliding contact follower with severe pitting damage

3.3 Scuffing

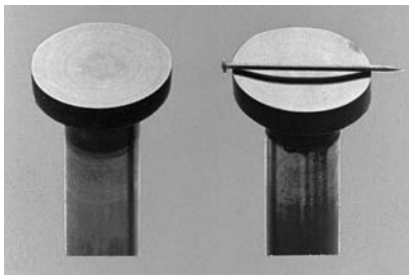
Scuffing is a severe form of adhesive wear caused by local welding of asperities on the contacting surfaces, particularly when a high degree of sliding occurs under poor lubrication conditions, followed by tearing apart of the welded material. A sudden increase in noise and vibration is often the first sign of scuffing. This may be followed by a progressive increase in the temperature of the contact and severe roughening of the contacting surfaces (see photograph). The onset of scuffing is poorly understood but it is usually associated with a breakdown in the protective films and oxide layers on the surfaces of the components in the presence of boundary or mixed lubrication (see Section 8.2). There is some evidence to suggest that scuffing occurs when the contact temperature exceeds a critical value (see Hirst, Reference 30). Scuffing is not primarily time-dependent and failure can be rapid once the process has begun. Further information on scuffing can be found in Barwell, Dyson, Hirst and Peterson (References 1, 10, 30 and 34, respectively).



The surface of a sliding contact follower with scuffing damage

3.4 Polishing

Polishing is a common type of mild abrasive wear in which material is removed from the surface asperities leaving a smooth burnished finish. This is a normal, and beneficial, process during running-in of the system but, under unfavourable conditions, it can continue indefinitely leading to removal of a large amount of material. Destructive polishing is likely if the lubricant contains wear particles or if the harder of the two contacting surfaces, is excessively rough. The existence of polishing wear may not be obvious from the appearance of the surfaces (see photograph) and the amount of wear may be revealed only after making measurements or by noticing poor performance of the machine.



The surface of a sliding contact follower with polishing damage

3.5 Internal Fatigue of Needle-bearing Roller Follower

An additional failure mode must be considered if a needle-bearing roller follower is employed. Like all rolling element bearings, these standard commercially available components have a finite fatigue life. A correctly-installed roller follower will eventually fail when either one of the internal rolling elements or one of the internal races is significantly damaged by pitting. Failures of this type can be recognised by rough, noisy running of the bearing followed eventually by seizure. It is possible to determine an estimate of the life of any rolling element bearing if the angular velocity and load experienced by the bearing throughout one operating cycle are known. In a cam/follower application the roller angular velocity and roller load vary continuously even when the cam rotates at constant angular velocity. A roller may fail prematurely if the load (static or dynamic) and/or the speed of the roller exceed limiting values stated by the manufacturer.

4. DESIGN PROCEDURES

4.1 Use of Flowcharts

An outline of the recommended sequence of actions required to make an informed choice of materials, manufacturing method and lubricant for a cam/follower system is shown on a pair of flowcharts (see Sketches 4.1 and 4.2). Sketch 4.1 illustrates the steps necessary to check the design of a system in which the cam/follower contact is essentially “sliding” (domed[†] or flat-faced[†] follower) and the corresponding procedure for a system with a roller[†] follower is shown in Sketch 4.2.

The procedures are based on the following principles.

- (a) For both rolling and sliding contact premature pitting can be avoided if the peak contact stress is less than the allowable values for the materials of both the cam and the follower.
- (b) Scuffing and polishing will not occur if surface contact is prevented by a lubricant film of adequate thickness.
- (c) Scuffing and polishing will be less likely to occur with rolling contact.
- (d) Premature internal fatigue failure of a needle-bearing roller follower is less likely if the modified life rating of that component is greater than the target life of the mechanism.

The procedures are essential for checking the design of cam mechanisms but each of the above principles is open to question. For example, grinding sometimes creates small surface cracks which can accelerate the pitting process. Scuffing can be prevented, even if the surfaces cannot be entirely separated by an oil film, if lubricant additives or special surface coatings are used. Many of these additional effects are identified in Sections 5 to 8, which can be read sequentially, although they are intended as notes explaining the steps outlined in the flowcharts.

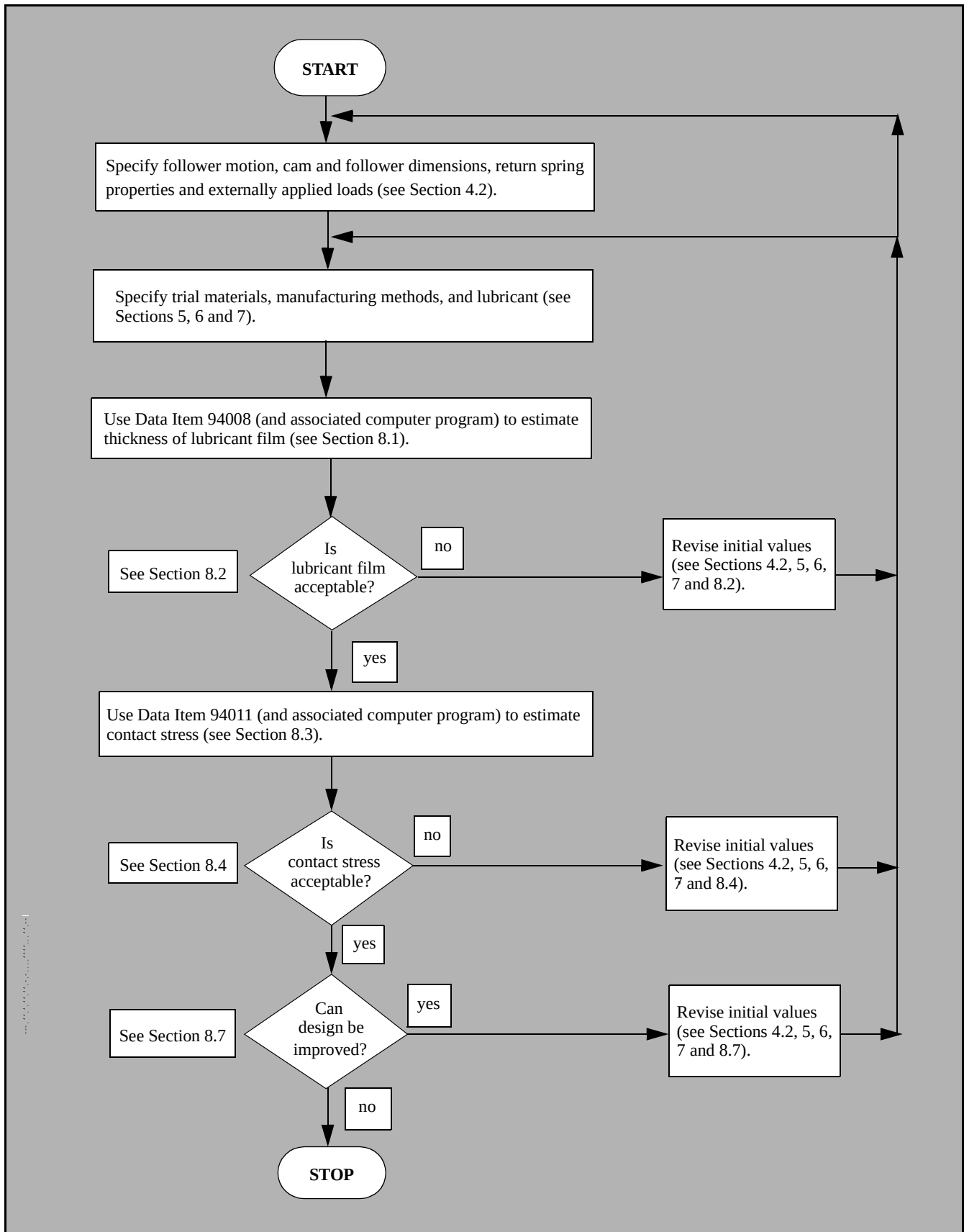
4.2 Specification of Motion, Geometry, Spring and Loads

The first step, in both procedures, is to specify the required follower motion. A suitable set of dimensions for the cam and the follower, such that the required motion is satisfied, should also be chosen. Important aspects of the required motion are usually stated in the mechanism design specification and methods for obtaining suitable initial values for the leading dimensions are given in Data Items 82023, 83008, 92005, 92014 and 93002 (References 13, 15, 21, 22 and 24, respectively). Further advice regarding the required format of the motion data, the cam and follower geometry, the specification of the return spring and the external loads is given in Data Items 91026, 93001, 94008 and 94011 (References 20, 23, 25 and 26, respectively). It is useful at this stage to decide tentatively on a required lifetime, or mean time between failures, for the system (in hours or in number of cycles).

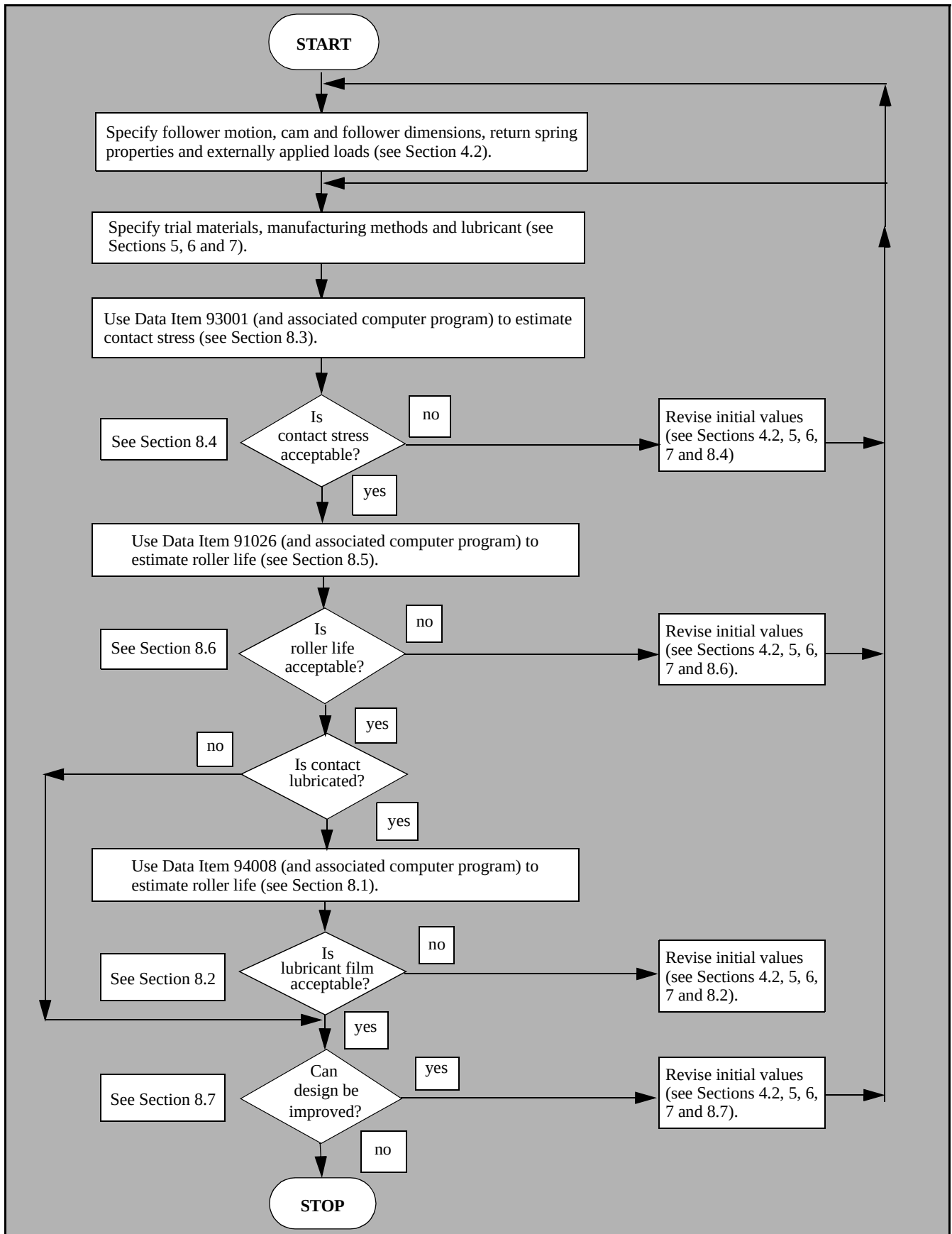
Each computer program associated with Data Items 91026, 93001, 94008 and 94011, that is used to evaluate the performance of the mechanism includes a method by which the stiffness and preload of a return spring (required to maintain contact) can be estimated. The final value of spring stiffness (taken from a spring manufacturer’s catalogue) should be chosen such that contact is maintained for all operating conditions. The worst case for spring design is usually “high speed with no load”.

The computer programs calculate contact load due to the inertia of the follower but externally-applied loads must be entered separately. It is not always easy to estimate these loads with confidence, especially at the outset of a design, and so it is wise to investigate the tolerance of the design to a wide range of values.

[†] The calculation procedures referred to in this Data Item are strictly applicable only to “crowned” followers (see Sketch 2.1) such that some misalignment of the cam and follower axes is tolerated. It is regarded as good design practice to include such a feature even with a nominally flat-faced follower. However the calculation procedures may be used to analyse mechanisms in which crowning is not present if a very large value of crown radius is specified.



Sketch 4.1 Design procedure (sliding contact)



Sketch 4.2 Design procedure (rolling contact)

This page Amendment A

5. MATERIAL SELECTION

5.1 General Comments

This section contains guidance on the selection of appropriate materials for the cam and the follower. This choice is dependent on a number of factors including the manufacturing route, the required life of the system, the loads transmitted across the cam/follower interface, the operating speed, the lubrication conditions, the chemical environment, the ambient temperature and economic considerations.

The choice of material has a direct effect on the likelihood of failure by pitting, scuffing or polishing. Ideally the materials used should be easy to machine, dimensionally stable (especially at high temperatures), self lubricating, resistant to corrosion and inexpensive. High values of surface hardness, Young's modulus and fatigue strength are desirable and the wear rate should be low. The properties of the surface layers are much more important in determining the useful life of a cam mechanism than the properties of the bulk material. However, the use of a different material for the surface layer is always constrained by the need to provide a very good bond between the layers and, as this is not usually possible, most successful surface treatments involve modifying the properties of the substrate by thermal or chemical treatment (see Table 6.2).

The desired life of the cam mechanism can have a significant influence on the choice of materials. In applications where maintenance is difficult and/or machine downtime must be avoided the use of expensive wear-resistant materials can be justified.

The design procedures (see Sketches 4.1 and 4.2) indicate that it is necessary to make an initial choice of material before determining the contact stress and the lubricant film thickness. Guidance on making this initial choice is given in Section 5.2 while information relevant to the final choice is presented in Section 5.3.

5.2 Initial Choice

Experience suggests that, for general industrial applications, other than those in which the loads and speeds are very low, hard metallic materials are most appropriate. It is important, especially for cam/follower systems in which there is significant sliding contact, that dissimilar materials are used because these are less likely to wear by adhesive processes. It is recommended that inexpensive materials be specified at the start of the design process.

To determine the contact stress (see Section 8.3) and the lubricant film thickness (see Section 8.1 if required) it is necessary only to decide on representative values of Young's modulus and Poisson's ratio for the materials of the cam and the follower. Therefore, at the feasibility study stage, it is necessary only to select the broad class of material for each component. Values of Young's modulus and Poisson's ratio for a range of materials are given in Table 5.1.

For general industrial applications in which small numbers of each cam are required it is recommended that a hardenable grade of steel be specified for the cam as this is usually a cost effective solution. Commercially available cam roller followers are widely used for this type of machinery, especially if the mechanism is not run in a bath of lubricant. The outer ring of this type of roller is usually made from hardened steel and so, if a hardened steel cam is specified, it is advisable to check with the bearing manufacturer that an alloy of the same specification is not used for the outer ring of the roller.

If the cam mechanism is to be made in large numbers the techniques of mass production, such as casting, forging or even sintering (see Section 6), become more cost effective and this will influence the choice of materials. Cast iron is regularly chosen as the material for automotive camshafts (in combination with hardened steel followers). Cast iron has other advantages, especially if sliding contact is expected, because its high carbon content leads to a self lubricating action which may reduce the risk of scuffing (see Table 5.2). The nose region of a cast iron cam is often chilled selectively during casting.

This leads to the formation of iron carbides which retain their high hardness at temperatures of up to 600°C thus increasing the resistance to scuffing failure (see Wilson, Reference 38).

TABLE 5.1 Typical values of material properties

<i>Material</i>	<i>Young's modulus (N/mm²)</i>	<i>Poisson's ratio</i>	<i>Comments</i>
Brass	100×10^3	0.33	
Bronze, phosphor	110×10^3	0.33	
Bronze, leaded	97×10^3	0.33	
Iron, grey cast	109×10^3	0.26	
Iron, malleable cast	170×10^3	0.26	
Iron, spheroidal-graphite	159×10^3	0.26	Has some self lubricating capability
Steel, low alloy	196×10^3	0.3	
Steel, medium and high alloy	200×10^3	0.3	
Steel, stainless	193×10^3	0.3	Difficult to achieve good surface finish
Steel, high speed	212×10^3	0.3	
Nylon	$(1.7 \text{ to } 2.8) \times 10^3$	0.4	Use for low speed/low load applications only
Tufnol	$(5.5 \text{ to } 6.8) \times 10^3$	0.38	Use sheet form with laminations at 90° to axis of cam rotation
Silicon carbide	450×10^3	0.19	Use for follower material only
Silicon nitride	314×10^3	0.26	Use for follower material only

TABLE 5.2 Relative failure resistance of some typical ferrous materials

<i>Material</i>	<i>Resistance to pitting</i>	<i>Resistance to scuffing</i>
Chilled cast iron	poor	good
Alloyed chilled cast iron		
Hardened alloy iron (flake)		
Hardened alloy iron (nodular)		
Flame hardened steel		
Case hardened steel		
	good	poor