Proceedings of The Institute of Acoustics

AN INVESTIGATION INTO CONSTRAINED LAYER MATERIALS FOR LOW NOISE DIESEL ENGINES

J.P.E. MOORES, R.G. FAULKNER and S.D. HADDAD

LOUGHBOROUGH UNIVERSITY OF TECHNOLOGY

SUMMARY

This paper reports on a project performed to evaluate two types of constrained layer damping treatments. After a brief description of the construction of the panels and the test procedure used, a broad overview of the results is presented.

The temperature characteristics of the panel damping behaviour observed are shown to depend on the viscoelastic material used. This in turn is related to the molecular structure of the polymer by explaining the significance of the glass transition temperature of polymers. Finally comments are made on the implications of this work to the design of constrained layer damping materials for low noise diesel engines.

INTRODUCTION

In recent years the use of road transport has increased significantly. With this increase traffic noise has become a very serious environmental problem. In many instances diesel-engined heavy commercial vehicles stand out as major noise contributors. Therefore much pressure is currently being applied to diesel engine manufacturers to reduce engine noise.

There are two broad approaches to reducing diesel engine noise:

a) Reduction of the mechanical impacts and combustion pressure levels which generate the noise, (1).

b) Reduction of the response of the engine components, (2).

The latter approach can be followed in several ways. Firstly a major redesign of the complete engine can be undertaken, (3), or secondly the engine can be enclosed in a soundproof box. A third alternative is that the response of the thin section components, which make up 40 to 50% of the engine surface, and include the rocker cover, timing gear cover, sump and manifold, can be reduced by damping treatments, (4). One such treatment involves the use of constrained layer damping materials. In these materials a viscoelastic material is sandwiched between two or more metallic layers. When flexed panels of this construction absorb energy efficiently by shear deformation in the viscoelastic constrained layer, (5) (see figures 1 and 2). Development of these materials specifically for diesel engine applications is currently in progress. This paper reports on one aspect of this work namely the investigation of two types of constrained layer materials.

AN INVESTIGATION INTO CONSTRAINED LAYER MATERIALS FOR LOW NOISE DIESEL ENGINES

EXPERIMENTAL PROCEDURE

Two types of constrained-layer-damped panels were tested. Type 1 panels had a viscoelastic layer constrained between an aluminium layer and a zinc layer of varying thickness applied by flame spraying. This treatment was developed for cast components, (6).

Type 2 panels had a viscoelastic layer of varying composition constrained between two steel layers. This material is intended to replace mild steel in pressed components.

Plain aluminium panels were also tested. Details of the panels used can be seen in Table 1.

The dimensions of the panels were chosen to give a fundamental frequency for an untreated panel of around 1000Hz. This frequency was chosen because it is in this region that diesel engines radiate most noise and also the human ear is most sensitive. The thickness of the type 1 panel's base layer was chosen to be that of a typical cast component.

The panel-loss-factor of each specimen was measured in the following manner. The panels were freely suspended in an oven and struck with a pendulum. The decay of the vibrations of the panels was measured with an accelerometer and recorded on polaroid film (typical results are shown in figure 3). The temperature of the panels was monitored with a thermocouple. Panels were tested at temperatures from 20°C to 120°C. The normal external operating temperature of diesel engines is above 100°C. For these measurements the A-weighting was used as a hi-pass filter (6).

The panel-loss-factor was calculated from the traces obtained using the equation

$$\eta_p = \frac{1}{N\pi} \log_e \frac{x_o}{x_N} \qquad \text{(Ref.7)}$$

x_o - initial amplitude
x_N - amplitude after N cycles
N - No. of cycles
η_p - panel loss-factor

The theory of constrained-layer-damping published by Beranek (7) was used to write a computer programme (8) which allowed theoretical panel-loss-factors to be predicted.

RESULTS

The panel-loss-factors of Type 1 panels are plotted against temperature in figure 4. There is a clear reduction in loss factor as the temperature increases for all these panels.

In figure 5 the loss factor of the type 2 panels is plotted against temperature. For these panels the loss factor generally increased with temperature up to 80°C. Panel P which was tested up to 120°C shows a peak at 80°C.

Figure 6 shows the effect of the zinc constraining layer thickness on the panel-loss-factor. Both the experimental and predicted values of loss factor show a peak.

Similar panels of type 1 construction were tested by discrete frequency analysis elsewhere (9) and a good correlation with the results reported here was obtained.

THE INFLUENCE OF PANEL GEOMETRY ON LOSS-FACTOR

Both theory and experiment indicate that the geometry of the panels has an effect on the damping performance. There is an optimum geometry, or more exactly an optimum relationship between the layer thicknesses, which gives maximum damping using a given viscoelastic material (see figures 4 and 6).

THE INFLUENCE OF THE VISCOELASTIC MATERIAL ON PANEL PERFORMANCE

The loss factor of a panel depends on its geometry and on the damping properties of the viscoelastic layer. The two important properties here are the shear modulus and the material-loss-factor. For panels where the geometry has been chosen to provide a high degree of damping the greater the material-loss-factor then the greater the panel-loss-factor. For a given geometry there is an optimum value of shear modulus; departure from this optimum causes a reduction in panel-loss-factor. The temperature dependence of these two properties of the viscoelastic layer dictates the way in which the panel-loss-factor changes with temperature.

THE TEMPERATURE BEHAVIOUR OF VISCOELASTIC MATERIALS

The change in storage modulus and loss-tangent with temperature (at constant frequency) of a polymer with high damping capacity is shown in figure 7. It can be seen that the peak in the loss-factor curve corresponds to a region where there is a sharp drop in the storage modulus. These changes occur at the glass transition temperature of the polymer (often denoted Tg).

An understanding of the significance of the Tg of the polymer must spring from an understanding of the molecular structure of polymers. Polymer molecules are giants. They consist of many small molecules (called monomers) which are linked together in long chains (as shown in figure 8a). These chains can consist of one or more monomer units. They can also be branched (figure 8b). This chemical structure of the polymer chain influences the physical properties of the polymer. The chain length and the interaction of chains in the polymer are also of importance.

The polymer chains can interact in a number of ways:

i) A random tangle of chains giving an 'amorphous' structure with interaction only at the tangles. See figure (9a).

ii) Polar chemical groups such as hydroxy-(OH) groups attached to the polymer chains cause alignment of chains and an increase in intermolecular forces and rigidity. See figure (9b).

iii) Chains with a very regular structure can pack closely together in aligned (crystalline) regions as shown in figure (9c) with a consequent increase in intermolecular forces and rigidity.

iv) Chemical bonds or cross-links can be formed between chains (figure 9d) giving a very strong and rigid structure.

The glass transition temperature is associated with a transition in behaviour of the amorphous regions of a polymer. At low temperatures only single atoms or small groups of atoms can move freely. In this condition deformation occurs by chemical bond stretching and rotation. At high temperatures large segments of polymer chains can move freely relative to each other in a liquid-like manner. The glass transition temperature is the temperature at which these large relative segmental movements start to occur.

Changes in physical properties at Tg can also be explained in molecular terms. Consider the two properties of interest for damping. The shear modulus is reduced at Tg because the restrictions on relative movement are reduced. This less restricted movement allows more energy absorbing mechanisms to operate and so the loss-factor is increased.

The glass transition temperature by its very nature depends on the structure of the polymer. Generally the greater the cohesive forces between molecules and the greater the hinderance to rotation by bulky side-groups on the chain, then the greater the Tg. The addition of plasticisers or fillers also affects the Tg. Glass transition temperatures in common polymers range from $-85^{\circ}C$ for polybutadiene to $170^{\circ}C$ for polycarbonate (12).

These changes in physical properties and a number of other methods are available to evaluate glass transition temperatures (12).

THE DIFFERENCE IN TEMPERATURE BEHAVIOUR BETWEEN TYPE 1 AND TYPE 2 PANELS

The results showed that the type 1 and type 2 panels exhibited markedly different temperature behaviour. This difference arose primarily because the polymers used in the viscoelastic layers had very different glass transition temperatures. The peak in panel-loss-factor corresponds with the glass transition temperature of the viscoelastic layer. For the type 1 panels this peak is probably below room temperature. For the type 2 panels the panel-loss-factor has a peak, for panel P, or is increasing, for panels M and N, at 80°C. Therefore the polymers used in these panels had Tg's of about 80°C or greater.

IMPLICATIONS FOR THE DESIGN OF CONSTRAINED LAYER DAMPING TREATMENTS

Much data exists on the structure composition and filler dependence of the glass transition of polymers. The correspondence between the Tg and the peak loss factor is also well demonstrated. This should allow initial selection and optimisation of polymers for use in constrained layer damping treatments for low noise diesel engine applications. It is however essential to remember other factors, such as the exciting frequency and the environmental resistance of the polymer. The possible use of Tg data for selection is important because of the lack of data on shear modulus and material-loss-factors.

CONCLUSIONS

a) The simple decay rate measurements on freely suspended panels excited by the impact of a pendulum offer a quick method for the evaluation of damping treatments at natural frequency.
b) The temperature dependence of the panel-loss-factor is a function of the damping properties of the polymer layer. The radical difference in temperature behaviour between the type 1 and type 2 panels is due to the different types of polymers used in their construction.
c) Optimisation of the treatments ought to be carried out by choosing the best polymer for the operating conditions.
d) There is a direct relationship between the Tg of a polymer and its peak loss factor. This should aid the selection of polymeric viscoelastic materials for use in constrained layer damping for diesel engines.

ACKNOWLEDGEMENTS

Thanks are due to Perkins Engines Ltd., who supplied much of the material to be tested and to the technicians in the Transport Technology Department at Loughborough University of Technology.

REFERENCES

1. A.E.W. AUSTEN and T. PRIEDE Symposium on Engine Noise and Suppression 'Origins of Diesel Engine Noise' Proc.Instn. Mech. Engrs., London, 1959, 173, 19.
2. S.D. HADDAD Ph.D. Thesis, Southampton, 1974.
3. T. PRIEDE, A.E.W. AUSTEN and E.C. GROIER 'Effect of Engine Structure on the Noise of Diesel Engines' Proc.Inst.Mech. Engrs., 1974, 179, 113.
4. M.F. RUSSELL 'Quiet Covers on a Perkins 6.354 with Standard Crankcase' CAV Report No. C29, 356, 1971.

5. J.A. AGABASIERE and P. GROOTENHUIS 'Flexural Vibrations of Symmetrical Multi-layer Beams with Viscoelastic Damping' J.Mech.Eng.Sci., 269, 10, 3, 1968.
6. PATENT applied for by Perkins Engines Ltd.
7. BERANEK (Ed.) 'Noise and Vibration Control' McGraw-Hill, 1960, Chapter 14.
8. J.P. MOORES, 'Evaluation of High Damping Capacity Materials for Low Noise Diesel Engine applications' Loughborough University, Final Year Project, 1980.
9. Private Communication with Perkins Engines Ltd.
10. A.E. HIRSH and R.J. BOYCE 'Dynamic Properties of Ethylene Acrylic Elastomers' Dupont Internal Report.
11. R.G. JONES 'The Polymeric State' Engineering, 674, July 1978.
12. F.W. BILLMEYER 'Textbook of Polymer Science' Wiley, 1971, Chapter 7.

* The storage modulus is the dynamic response equivalent of the shear modulus.

TABLE 1 DESCRIPTION OF PANELS TESTED

PANEL	BASE LAYER		VISCOELASTIC LAYER		CONSTRAINING LAYER		PANEL SIZE			TYPE
	HEIGHT H_1 ~ mm	MATL.	HEIGHT H_2 ~ mm	MATL.	HEIGHT H_3 ~ mm	MATL.	HEIGHT H ~ mm	LENGTH L ~ mm	WIDTH B ~ mm	
A	3.25	Al.	-	-	-	-	3.25	350	73	PLAIN
B	3.25	"	-	-	-	-	3.25	315	73	"
C	3.25	"	-	-	-	-	3.25	212	75	"
D	3.25	"	-	-	-	-	3.25	315	85	"
E	3.18	"	-	-	-	-	3.18	300	100	"
F	"	"	0.4	W	1.3	Zn	4.88	300	100	TYPE 1
G	"	"	"	"	3.0	"	6.58	"	"	"
H	"	"	"	"	5.3	"	8.88	"	"	"
K	"	"	0.1	"	3.2	"	6.48	"	"	"
L	"	"	0.4	"	0.3	"	3.88	"	"	"
M	0.52	STEEL	0.10	X	0.52	STEEL	1.14	290	"	TYPE 2
N	0.45	"	0.20	Y	0.46	"	1.12	"	"	"
P	0.51	"	0.12	Z	0.51	"	1.14	"	"	"

AN INVESTIGATION INTO CONSTRAINED LAYER MATERIALS FOR LOW NOISE DIESEL ENGINES

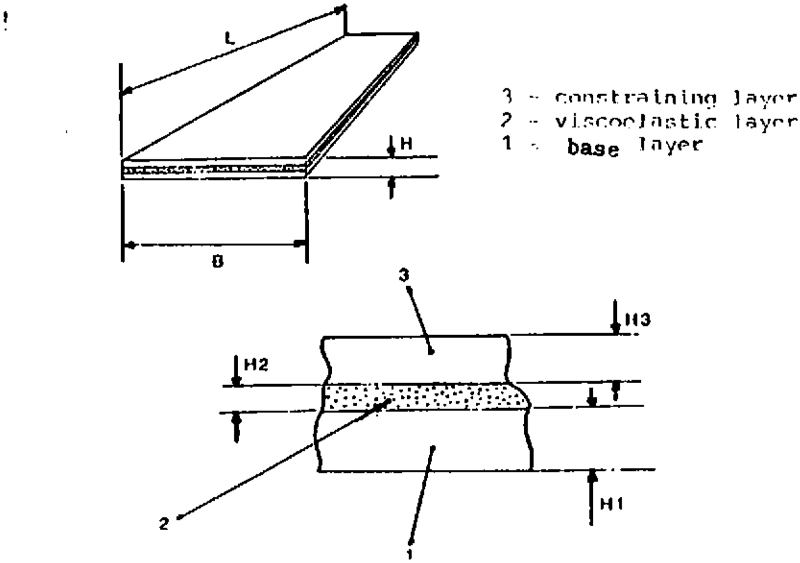

Figure 1 A Diagram of a Panel with Constrained Layer Damping

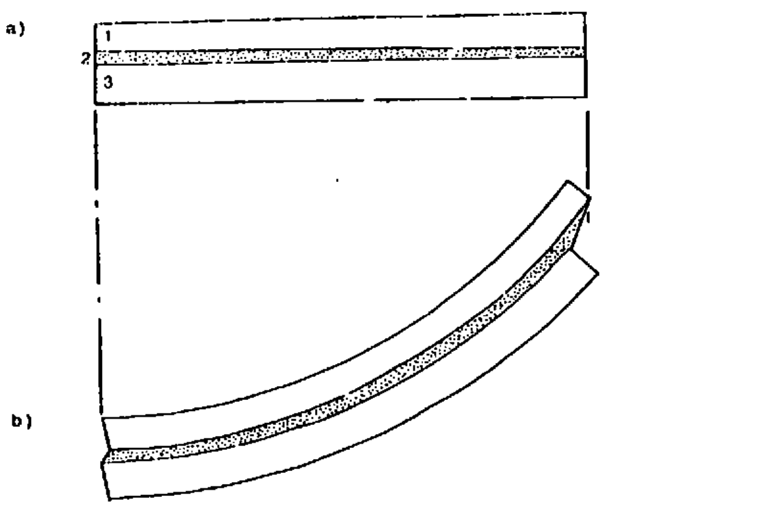

Figure 2 Section of a Panel With a Constrained Viscoelastic Layer a) flat; b) deformed. Note the large amount of shear in the viscoelastic layer on deformation.

(a)

(b)

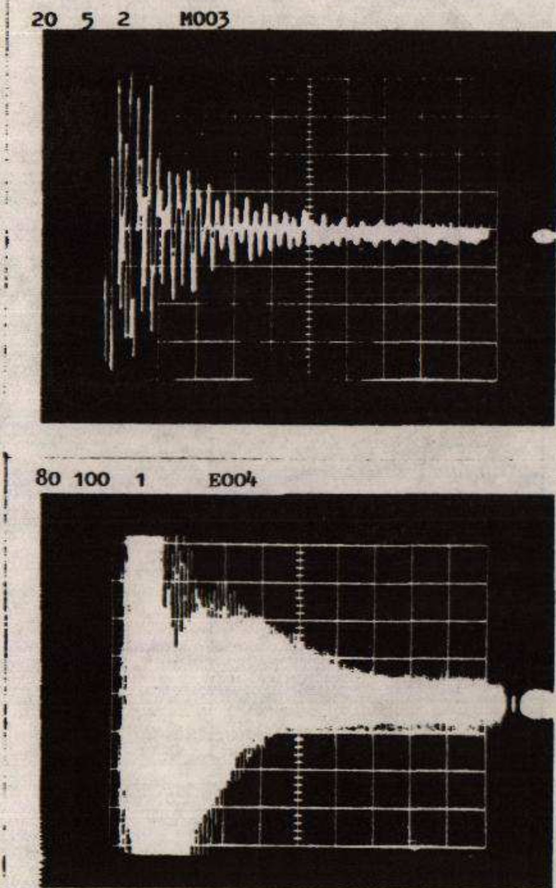

Figure 3 Typical Decay Rate Measurements
a) Time constant is 5 ms/div. - Panel M
b) Time constant is 100 ms/div. - Panel E

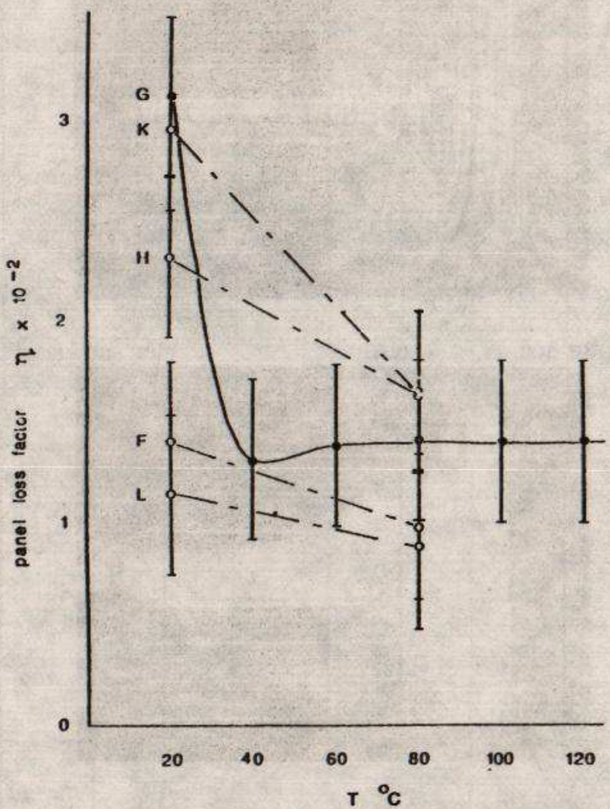

Figure 4 The Panel Loss Factors of the Type 1 Panels Plotted Against Temperature. A continuous curve is plotted for panel G.

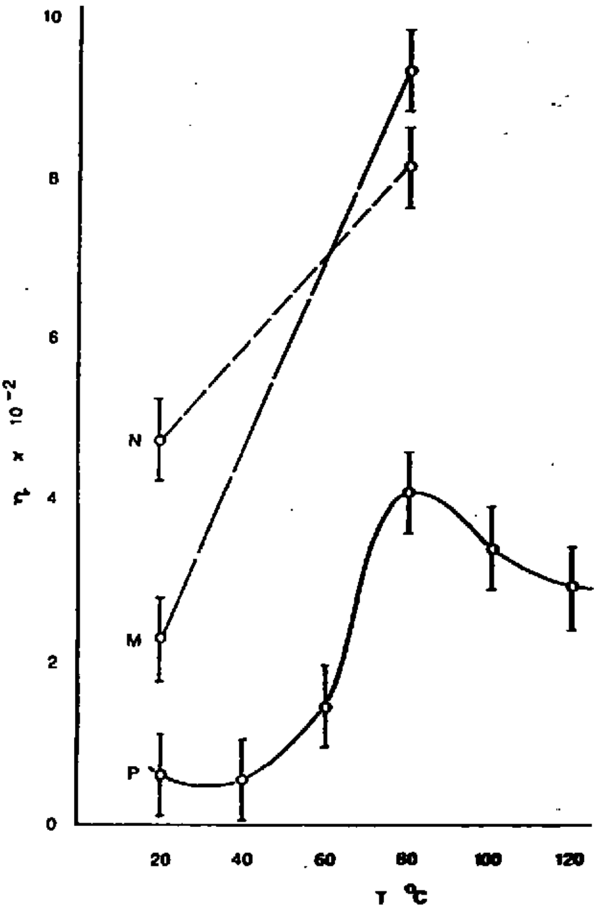

Figure 5 The Panel Loss Factors of the Type 2 Materials Plotted Against Temperature. A continuous curve is plotted for panel P

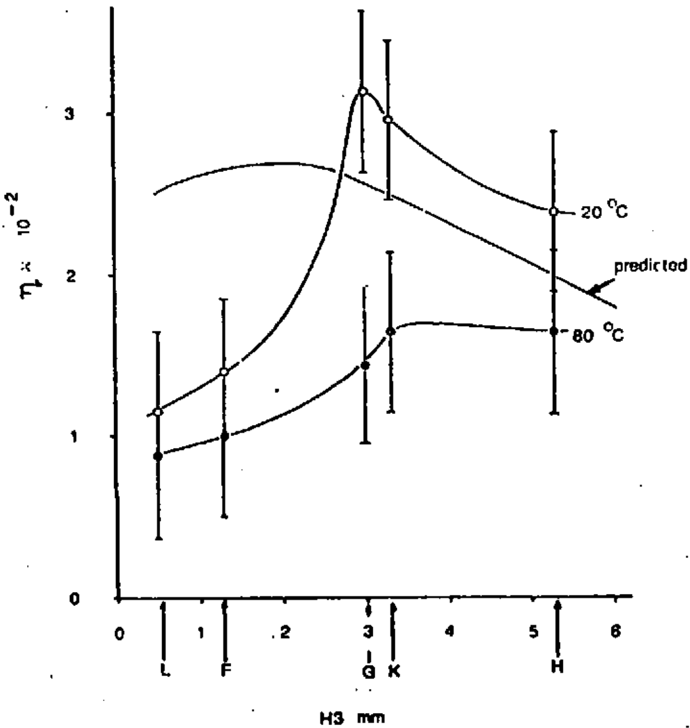

Figure 6 The Experimental Values of Loss Factor of the Type 1 Panels Against H3 — The Zinc Constraining Layer Thickness.

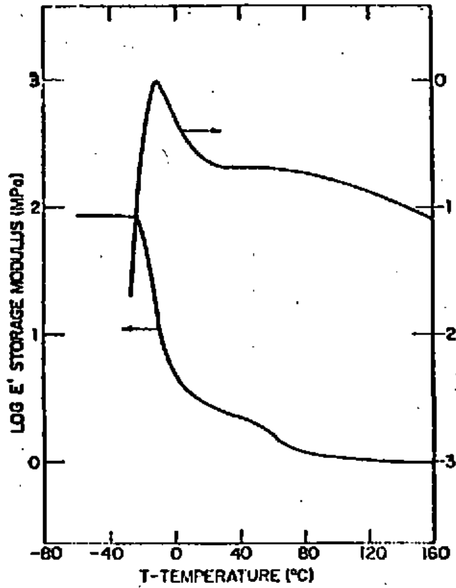

Figure 7 The Storage Modulus and Loss Tangent of an Ethylene/Acrylic Elastomer as a function of temperature. The Storage modulus is the Dynamic response equivalent of the shear modulus. The loss tangent is effectively the loss factor (10). .... Note the log scale.

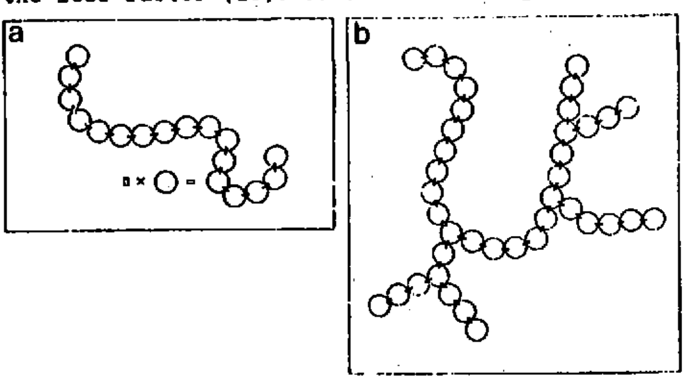

Figure 8 a) A polymer chain made up of many monomer units
b) A branched polymer chain

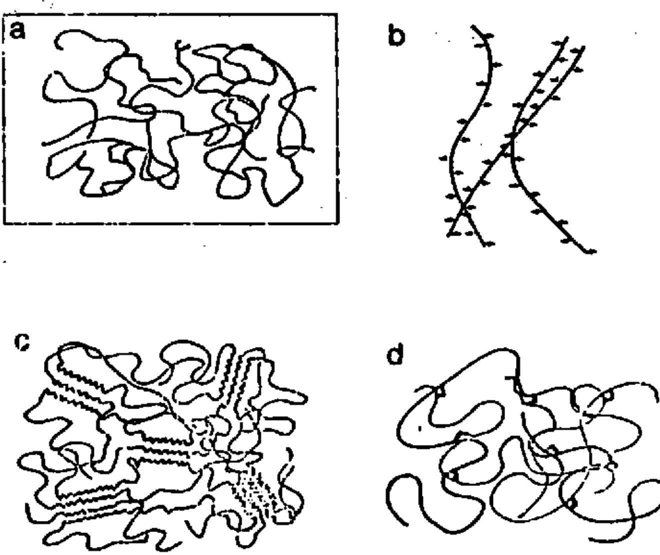

Figure 9 The Different Ways in Which Polymer Chain Molecules Interact (11)

a) An amorphous polymer
b) Attraction between polar groups
c) Crystalline regions
d) Crosslinked chains