DENTURE BASE MATERIALS

A Critical Review of Recent Literature
This critical review of recent literature concerning Denture Base Materials is submitted in support of candidature for the Degree of Master of Dental Surgery.
"I am part of all that I have met;
Yet all experience is an arch
wherethro' Gleams that untravell'd world,
whose margin fades
For ever and for ever when I move."

Tennyson (193)
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INTRODUCTION
THE DENTURE BASE

There has been a constant search to obtain a denture base material of lifelike appearance that would not deteriorate in service. Before the advent of acrylic resin rubber had been the most satisfactory material available for almost 75 years. Celluloid was also used in this period. It had a more pleasing initial appearance than rubber but soon warped and discoloured and was otherwise unsatisfactory (187). The denture bases available at this time are largely methyl methacrylate resins to which is added, in some cases, ethyl methacrylate or ethyl acrylate or another of the acrylic resins. There are a few products in which the vinyl resins are added, or which make use of styrene monomer with methyl methacrylate polymer (121). Several new types of polymer have also been introduced with the intention of overcoming the disadvantages of the methacrylate resins (167).

Since the introduction of the acrylic resins for use in dentistry there has been a continual search for modified practices in processing the resins which will lead to improved qualities in the finished structure (121).
2.

A denture base material must facilitate the production of dentures and bring them within the reach of the average person; it must combine ease and speed of manipulation with resistance to contamination and deterioration under mouth conditions (214).

It is necessary to list the desirable properties of a denture base material in order to evaluate the available materials as denture bases, and to determine how they might be improved (198).

1. **Tissue Tolerance:** The material must be non-allergenic. Toxic compounds are frequently present in denture bases, e.g. the selenium in the pigments of resins. The selenium in the synthetic resins is so held by the body of the material that there is a infinitesimal amount of it on the surface, and the toxic effect is negligible (79, 86, 198).

2. **Absence from objectionable taste and odour:** The base material should not absorb or retain tastes and odours of foods, beverages, or medicaments. It should not become fouled by absorption of water. Although water sorption should be as low as possible, molecular water can be imbibed without the dentures becoming foul. Certain types of material with a looser molecular lattice are
rendered foul by absorbed water and accompanying bacteria \( (79, 198) \).

3. **Strength:**

(a) Flexural fatigue strength should be high as many of the forces to which a denture is subject are of a flexural nature. It has been variously estimated that a person bites on an average 500,000 times per year. The danger of fatigue failure occurring in prosthetic restorations would thus seem to be a real one, \( (39, 72, 79) \).

(b) Impact strength: This should be high as even the most careful of patients may drop a denture. Perhaps also, a denture fracture while the patient is chewing a hard nut or some similar food could be regarded as an impact fracture, \( (6, 220) \).

(c) Transverse strength should be sufficiently high so as to allow a thin section which is neither fractured nor distorted by occlusal force. The material should not be brittle but should be sufficiently hard to withstand reasonable usage \( (79, 86, 191) \).

4. The material must be easy to manipulate with accuracy, and must retain its shape permanently. It must reproduce all recorded detail accurately, and have a minimum
of dimensional change during processing, following insertion and during use. Moulding and processing must be possible with simple equipment. There should be a minimum of inherent variables in the polymerisation behaviour of the material (6, 191, 198).

5. A hard surface which is resistant to abrasion is necessary so that the material will take and retain a high polish (6).

6. The softening temperature should be well above mouth temperature, indeed it would be ideal if the denture could be sterilized by boiling (6).

7. The material must be easy to repair and should not distort when repaired. The repaired material must have adequate strength (6, 117).

8. A denture base should be impermeable to oral fluids. When a polymer absorbs water it is literally undergoing changes of constitution, dimension and other properties (6, 104).

9. Low specific gravity with a high thermal conductivity.

10. The material should resemble gum tissue in colour and translucency, and the colour must be permanent (6).
5.

It has not yet been possible to discover a material which fulfils all these requirements. Many materials have been tried but have been discarded because they were unsatisfactory from too many aspects (6). It is time that dentists stopped accepting the manufacturers' word that the best possible denture base materials are now available. Base materials do change in significant amounts even though the measurements are said to be small. If the tissues covered by the dentures were hard then no dentures would fit (19). Until we are able to control absolutely the volume changes inherent in our impression materials and denture bases, we can never produce a really perfect set of dentures (18).

There is no ideal denture base, although poly-methyl methacrylate resin is regarded by most practitioners as the nearest approach to date. Where it fell short of the ideal six or seven years ago, it still falls short today, although there have been numerous attempts and suggestions made to improve it. Its chief disadvantages of relative softness when compared with tooth enamel, dimensional changes on processing, and susceptibility to attack by organic liquids still apply (39). One of the criticisms of methyl methacrylate type of dental resins is a tendency for fracture (71). This tendency is thought
to be coupled with the flexural fatigue resistance of the material, such that the greater the value of flexural fatigue resistance in the material, the greater will be its resistance to mid-line fracture (72).

Smith (163, 167) claims that heat-cured acrylic resin is adequate in its impact strength and flexural strength for 90 to 95% of denture patients, and that the cause of fracture of acrylic denture base is very often not a fault of the material but is the result of deficiencies in design and/or construction.

It is clear (167) that the ideal situation of a completely acceptable dental polymer is still far from being reached. Some dentists claim to overcome such inadequacies by employing a cast metal base. Yet a metal base will not necessarily fit the cast better than an acrylic base. In fact, recent data (7) indicates rather poor accuracy for some of the cast chromium-cobalt alloys.

Only more extensive clinical and laboratory research can provide a satisfactory answer to the problems of "The Denture Base".
7.

The Testing of Dental Materials: Clinical testing of dental materials is an important method of determining their usefulness in dentistry (56). However, in a progress report of more than twenty years ago (163) Sweeney & Schoonover wrote:

"The need for the dentist to have some method other than clinical for judging the relative merits of different materials is apparent to anyone who reviews the literature and who is familiar with the experience of the profession. Failure of so many of the materials sold during the past few years to live up to glowing advertising claims has meant bitter disappointment. During the past ten years more than thirty different trade brands of materials other than vulcanites have been offered for sale to the dentist. The scheme of having the dentist test all these materials clinically has been unfair to both the dentist and patient and has been very expensive."

The faults of the current and the allegedly improved materials which are offered to us can only be judged in terms of their clinical suitability, against a background of our fundamental requirements, and not by a simple superficial comparison, as is often done. Tests designed to reveal the effects of manipulative variables or
to compare different materials will have little practical value unless the tests are specifically related to the stress conditions and environment involved in service. So our clinical assessment must be based upon properties determined at mouth temperature ($37^\circ$C) under wet conditions and by the subjection of the material to dynamic forces (163).

Many of the failures that resulted in dentures made of the earlier resin plastics could have been avoided if there had been a satisfactory standards comparison available and if the products had been tested in the laboratory before being exploited (187). A realistic appraisal of the mechanical properties of denture base materials can be carried out only on a basis of the clinical requirements for the material (162). In spite of the large volume of laboratory research and clinical experience which has been accumulated, little attempt has been made to interrelate these in order to provide a firm basis for assessment of the new materials and to expose inherent faults (faults other than those due to incorrect manipulation) of the acrylic materials (164). In most of these investigations conventional methods of plastics testing have been applied to dental polymers for comparative purposes (usually under room conditions) with the implicit
assumption that the relative merits so obtained were a guide to service behaviour. Although a considerable advance in our knowledge has resulted from this and other work, it has become evident in recent years as knowledge of the complex behaviour of plastics has accumulated that such testing has in fact, little practical value unless the test conditions are specifically related to the stresses and environment that exist in the mouth (162).

This review of the recent literature on denture base materials has been conducted with the view to correlating the results of a large number of experiments, that have been carried out by many researchers and under widely varying conditions. Many materials have been tried by the profession but have been discarded because they were unsatisfactory from too many aspects (6).

It is not the purpose of this review to record unsatisfactory materials, but to assess the limitations of the current denture base resins, and the testing procedures that are used to evaluate these materials, and to suggest in which venue further research is most likely to be successful in the seemingly never-ending search for a non-biologic material that can be used as an adequate denture base under all conditions.
SECTION 1

DENTURE BASE RESINS
PLASTICS:
A generic term - given more by common usage than by any etymological right - to those synthetic materials which are based on a high polymeric organic substance, and which can be transformed into various solid shapes through a process of moulding, forming, extruding or casting, usually by the application of heat and pressure (52).

A POLYMER: Usually described in terms of its structural unit (or monomer). Structural units are groups having two or more available bonding sites and are linked to one another through covalent bonds in a polymer molecule. The units can be arranged and connected in a variety of ways. In the most straightforward type of polymer, the LINEAR POLYMER, the units are connected to one another in a straight chain arrangement (177).

Polymers are formed by two methods:
CONDENSATION POLYMERIZATION where there is usually a bi-product formed and growth is by the addition of various sized chains to variable sized chains. A condensation polymer does not have the same composition as the monomer or monomers from which it was formed,
or to which it may be degraded by chemical means.

VINYL POLYMERIZATION OR ADDITION POLYMERIZATION:
Monomeric units add on to chains at one or both ends basically in unit fashion.

The FUNCTIONALITY of a molecule is the number of groups it contains which can condense to form a bond with another molecule. BIFUNCTIONAL molecules lead to the formation of long chains or linear polymers. The length of the chains can be terminated by the addition of some monofunctional compound (or monovalent impurity). The size of the chain is decreased in proportion to the amount of monofunctional material added.

When trifunctional molecules are present, branching of the polymer molecules can occur and these can become interconnected to form a network. These materials are CROSS-LINKED and are usually insoluble and infusible. Only a small number of trifunctional molecules are necessary in order to obtain cross-linking. If a polymer has one hundred units in its chain, one trifunctional segment will serve to cross-link it and repetition of this structure will result in a gel structure.

When polymerization has finished there will be a greater concentration of a polymer of a certain size and
reducing concentrations of all polymers above and below this size.

Polymers containing a single repeating unit such as polystyrene are referred to as HOMOPOLYMERS. On the other hand, polymers containing two or more structural units, which may be joined in recurring or random arrangement, are COPOLYMERS (177).

If monomer is to be stored inhibitors are frequently added in order to prevent premature polymerization. Copper salts, sulphur compounds or polyhydric phenols such as hydroquinone are added to stabilize vinyl monomers. These inhibitors prevent the formation of chains by acting preferentially with any initiator that should accidentally become activated (125).

Polymerization is TERMINATED in any one of three ways:

1. Bimolecular coupling of two growing chains.
2. Disproportionation; through transfer of a hydrogen atom (free radical) from one growing chain to another.
3. Chain Transfer: through transfer of a hydrogen atom (free radical) or other atom of the solvent or other molecule foreign to the growing
chain, e.g., an impurity (179).

A polymer is terminated by a monovalent molecule whereas the monomer molecule must be bi-valent or BIFUNCTIONAL so that it can join with two other monomers.

The DEGREE OF POLYMERIZATION: Describes the molecular size. High molecular weight polymers have varying degrees of polymerization or molecular weight distribution among the chains within an individual polymer batch (177).

PLASTICISERS: The effect of plasticisers on denture base resins with particular reference to acrylic resin.

Any substance interposed between the chains of a polymer decrease the strength unless the substance serves as a cross-linking agent. By separating the chains, or by lying between, plasticisers decrease the intermolecular forces of attraction. (These intermolecular forces are usually polar). Plasticisers make the solid more plastic, more liable to flow, and less brittle. Polymers used in the mouth frequently contain two unwanted plasticisers - residual monomer and water. Water, which is highly polar, may readily penetrate polymers and, the poles of water neutralise the poles of the polymer molecule (136). Plasticisers reduce fatigue strength, impact resistance,
hardness, and solvent resistance (138, 167). Cornell, Tucker and Powers (31) tested two types of plasticiser (aromatic, and aliphatic) and found that water considerably lowered impact resistance and plasticisers slightly so. Impact resistance results were the same regardless of whether the plasticiser was added in the polymer or in the monomer.

Plasticisers are essentially softening agents and they lower the physical properties of methyl methacrylate, (199). For this reason, apart from the use of cross-linking agents and copolymers, dental acrylic resins are kept relatively free of modifying agents (39).

**COPOLYMERISATION** and **CROSS-LINKING** with particular reference to acrylic resin denture base materials:

**COPOLYMERISATION**: When two or more vinyl compounds are polymerised at once a mixed polymer results. Such a polymer is a copolymer and segments of both monomers are present. Not all mixtures of vinyl compounds will form copolymers and, if their rates of polymerisation are greatly different the faster material will polymerise first and a copolymer will not result. A copolymer is a complex and has properties different from either polymer alone (125, 204).

Copolymerisation of methyl methacrylate with other
monomers produces a mixed result in that some particular property may be improved (for a particular purpose) whilst others are made worse, e.g., copolymerisation with other acrylic monomers usually gives tougher, more resilient products having lowered strengths and heat resistance, (163). However, dynamic properties such as fatigue resistance may improve. Matthews and Tyldesley (99) tested a copolymer resin (Copol) which is said to be a copolymer of ethyl methacrylate and methyl methacrylate in the approximate proportions of 1:11. They found that the flexural fatigue resistance was much higher than that of the ordinary acrylic resins tested with comparable tensile strength and hardness values for all specimens. However, it is to be noted that the tests carried out by Matthews and Tyldesley were done at room temperature and humidity rather than under mouth conditions.

CROSS-LINKING: Very commonly copolymerisation is accompanied by cross-linking between molecular chains (3). For this to occur the copolymerising monomer must be tri or poly-functional. Usually the powder is non-crosslinked, and a cross-linking monomer is added in the usual manner. A large number of cross-linking monomers is available, but divinylbenzene and ethylene glycol dimethacrylate and other dimethacrylates appear to be
most commonly used (167). In general cross-linking lowers strength and flexibility but increases solvent resistance, softening point, and hardness. Fatigue and impact strengths are usually lowered, but Cornell et al (31) find a very significant increase in impact strength particularly at 10% of cross-linking agent (ethylene dimethacrylate). The improvement in impact resistance reached its limiting value at 10% of cross-linking agent and thereafter with increasing amounts of cross-linking agent the improvement in impact strength was small.

Harris (64) found that pure poly (methyl methacrylates) showed a tendency to craze, copolymers showed a slight degree of crazing, and the cross-linked materials apparently show no change when used with immediate reliners under mouth pressure and mouth temperatures. Smith (163) reports that cross-linking gives sufficient solvent resistance to avoid crazing, but the tensile and fatigue strengths are lowered and there is little practical improvement in water absorption, hardness, and abrasion resistance. Wollff (224) stored specimens in water and carried out tests at room temperature. He found that the tensile strength of cross-linked specimens appeared to increase slightly with increasing amounts of cross-linking agent in the monomer up to 25%, after which there was a
definite decrease in strength. He found that the recovery of cross-linked specimens after indentation was higher than for pure poly (methyl methacrylate) and that no other significant improvement in the mechanical properties tested was obtained by the use of cross-linking agents. Rose, Lal, Green and Cornell (133) found that the water sorption of acrylic resin did not vary significantly with cross-linking. Landry, Mirza and Erdle (88) found that the use of a cross-linking monomer lowered the processing error of acrylic resins and increased the stability of palate fit. No data was given but it is likely that the differences were small.

One disadvantage of cross-linking is the reduction of bonding between acrylic resin teeth and the base, which may occur particularly with a cold-curing base material. This is very important since a fatigue fracture starts with a crack between teeth and base material (167).

Thus it would appear possible to achieve a significant improvement in impact strength (Cornell et al (31)) and flexural fatigue resistance (Matthews and Tyldesley (99)) in dough moulded dental acrylic resins with the use of about 10% cross-linking agent. It is hoped that these improvements can be attained without the reduction of other properties. However, more tests related more closely to
oral conditions are necessary before a definite decision on cross-linking can be made.

**VINYL POLYMERISATION:** The polymerisation reaction proceeds as does any other chemical reaction (125). Vinyl polymerisation is a chain reaction and features an active site on the end of a growing chain.

\[
\begin{align*}
M + I^* & \rightarrow IM-M^* \\
M & \rightarrow IM_2M^* \\
I-(M)_nM^* & 
\end{align*}
\]

I* can be some free radical initiator, cationic initiator, or anionic initiator. In this type of polymerisation reaction the synthesis of a polymer molecule is very fast and the overall conversion of all the monomers to polymer chains is slow, so that there are few low or intermediate molecular weight polymer molecules (177).

There are many factors which determine the physical properties of simple molecules as well as polymer molecules. Some of the most important of these factors are molecular weight, the nature of the primary and secondary valence bonds, the symmetry and arrangement of the molecule. These factors influence the crystallinity of the molecule, which in turn, and in combination with these factors, determines such simple physical properties as melting point, tensile strength, solubility, etc. (178).

The molecular weight and the molecular weight
distribution of polymers plays an important role in the physical properties of the polymer. In general a narrow molecular weight distribution gives more useful polymers. The softening point and tensile strength of a polymer can be related to its molecular weight and other structural features. Within a given polymer, the melting point and tensile strength increase as the molecular weight increases, as shown in Fig.1.
At lower molecular weights the melting point and tensile strength are very much affected by the molecular weight. At some molecular weight which is characteristic of the individual polymer, a break in the curve occurs and higher molecular weights have a lesser effect on the properties of the polymer (178).

In general the milder the conditions of polymerisation the larger the polymers that are formed. If many chain reactions are started the more likely it is that two of these will collide and so form a short complete chain. It is generally accepted that larger molecules are produced as the temperature of polymerisation is decreased (28). If too high temperatures are employed there will often not be any polymerisation. At temperatures above 250°C, many vinyl polymers break down and the monomer may be recovered. Impurities, particularly when they are able to stop the growth of chains, often result in the formation of lower polymers. The size of the polymer formed is also dependent on the degree of activity of the catalyst used and the amount of catalyst that is present. The larger the amount and the more active the catalyst the smaller will be the polymer formed as a large number of chain reactions will have been started at once. The conditions which give the most rapid rate of polymerisation also lead to the smallest polymers (126).
CHAPTER 1.

HEAT CURED ACRYLIC RESIN: In the dental profession poly (methyl methacrylate) resin is used extensively as a denture base (26, 29). Since the introduction of the dough process over twenty years ago, the polyesters of acrylic acid, substituted acrylic acids, and copolymers of these resins with the vinyl esters have almost entirely supplanted other materials (164, 184, 218). The most widely used of these resins is poly (methyl methacrylate). However, since the introduction of this material as a denture base material in 1937, there have been many suggested variations in the techniques of processing this material, with several additional materials proposed, in order to overcome the deficiencies that are thought to occur in the acrylic materials, (122, 164). Often these variations have been introduced with a claim of superior properties, improved accuracy of fit, and greater dimensional stability in service (219).

By 1942 poly (methyl methacrylate) resin with some of its copolymers was claimed (by Souder and Paffenbarger) to be the most satisfactory denture base material available. A similar statement about the
satisfactory qualities of acrylic resins used as denture bases might well be made at this time (218). This long continued dominance (119) of poly(methyl methacrylate) is due to the fact that no other resin - and there have been hundreds of them - has been developed that has superior properties for use as a denture base resin and that can be processed with a simple technique using plaster-of-paris moulds (120, 219).

In spite of the excellence of the acrylic materials many difficulties have been reported: among them, water absorption, dimensional instability, brittleness, discoloration, difficulty of repair, liability to mid-line fracture, producing sore mouth and bubble formation (26, 163). These difficulties for the most part are not inherent properties of acrylic resin but are defects induced in it by improper processing. It is believed that variations in physical properties and some of the other difficulties observed in acrylic dentures are associated with the nature and completeness of polymerisation and the possible retention of monomer (26, 164).

Methyl methacrylate is prepared commercially by the addition of cyanide to acetone with a potassium hydroxide catalyst, followed by a hydrolysis, dehydration, and an esterification step to yield methyl methacrylate
monomer. The intermediates in the reaction are not isolated but the reaction is carried to completion (182).

\[
\begin{align*}
\text{CH}_3\text{COCH}_3 & \xrightarrow{\text{HCN}} \text{CH}_3\text{C}=\text{C}-\text{CN} & \text{H}_2\text{SO}_4 & \xrightarrow{\text{CH}_3\text{OH}} \text{CH}_2=\text{C}-\text{CO}_2\text{CH}_3
\end{align*}
\]

Methyl methacrylate polymerises readily at a temperature of 70 to 75°C in the presence of the commonly used catalyst, benzoyl peroxide. At these temperatures the exothermic heat of polymerisation begins to be liberated and is added to the external heat supplied by the bath (173).

Heat or light will decompose the catalyst benzoyl peroxide to a phenyl radicle. This will combine with a vinyl monomer but in doing so the double bond in the monomer is opened and a further active site created.

Benzoyl \[\text{heat} \rightarrow \text{Phenyl} \text{vinyl} \text{initiated}\] peroxide \[\text{light} \rightarrow \text{radicle} \text{monomer} \text{polymer}\] chain

\[(\text{C}_6\text{H}_5\text{COO})_2 \rightarrow \text{C}_6\text{H}_5^m + \text{CH}_2=\text{C}-\text{COOCH}_3 \rightarrow \text{C}_6\text{H}_5\text{CH}_2=\text{C}-\text{COOCH}_3^m\]

If \(m\) represents one activated benzoyl peroxide molecule, and

\(M\) represents the basic methyl methacrylate structure

\[
\begin{align*}
\text{CH}_3 & \quad / \\
\text{CH}_2=\text{C}-\text{COOCH}_3
\end{align*}
\]
Then the polymerisation reaction could further be represented as:

\[
\begin{align*}
I^W + M & \rightarrow M_1^W + M \\
\rightarrow M_1^W \\
M_2^W + M & \rightarrow M_3^W \\
\end{align*}
\]

etc. (179).

HEAT CURED ACRYLIC RESIN - METHODS OF MOULDING:

COMPRESSION MOULDING: Acrylic resin is supplied to the dental profession for compression moulding as a powder (small particles of polymer) and as a liquid (monomer) (26). In the process of polymerisation most of the original polymer granules remain in the final material embedded in a matrix of newly formed polymer (166). The liquid should be water clear and free of deposits or sediment (184). The monomer is variously estimated to contain 0.002% to 0.01% of hydroquinone as a stabiliser, (63, 136, 164).

The grains of powder are made by emulsion polymerisation: Monomer is dispersed in water, benzoyl peroxide added to the emulsion, and the mixture is heated. The benzoyl peroxide is activated by the heat and initiates chain formation in the small droplets of monomer. Thus
pearls of polymer are formed, and in these pearls will be
traces of the chain initiator, benzoyl peroxide.
Inorganic dyes may be added so that the pearls will contain
or have attached, a small inert coloured particle. The
size of the pearls will depend on the degree of dispersion
of the monomer (136). Powders have been analysed and
found to contain between 0.2% and 0.9% of benzoyl peroxide
(63, 164).

MIXING THE POWDER AND LIQUID: It is considered
important that the powder be added to the liquid (36, 121)
(205). With many products the instructions for mixing
the powder and liquid are inadequate. The proportions
often are given as three volumes of powder to one volume
of liquid to give a suitable ratio for the mass (36, 121).
Smith, (164), used a material for which the manufacturer's
instructions recommended a volume ratio of 3.5 parts of
powder to 1 part liquid. Horton (68) claims that the
monomer should be reduced as far as practicable, a 4:1
polymer monomer mix is advisable in order to minimise
strains that arise from the contraction of the resin
during polymerisation. An equally accurate practice, and
generally a more convenient one, is that of measuring the
desired amount of liquid into a measuring jar and adding
to the liquid all the powder which it is possible for the
liquid to wet. The jar should be tapped and powder added till no more residual liquid is visible on the surface. Peyton (121) found that mixes made in this manner were as reproducible for the total amount of powder wetted by the liquid as when the powder and liquid ratio was measured by volume. Sufficient liquid must be present to wet the powder thoroughly (36). Peyton (121) found that 10cc. of liquid wet between 29 and 36cc. of powder when he conducted a survey of four brands of acrylic resin.

In the case of the heat-cured materials, the doughing process is due simply to the dissolution of part of the polymer in the monomer; no appreciable polymerisation takes place until the dough is heated (162). In general, the more liquid that is present in the mass:

1. the longer is the time required to reach the suitable packing consistency at any given temperature.

2. the greater is the tendency toward porosity in the finished product when a fixed curing practice is followed (121).

3. the greater the dissolution and swelling of the polymer -- with a resulting slight increase in strength, BUT

4. with a bigger curing shrinkage (162).
The dough is deemed to have reached a satisfactory consistency for packing when the plasticity is such that the resin separates cleanly from the walls of the glass mixing jars (184, 164). When the mass has developed a suitable consistency for packing, it is most practical to use a mould that is at approximately room temperature. If the flask or mould is at a higher temperature the resin of the powder-liquid type tends to become stiff before the flask is completely closed (121). Overpacking of the mould may be a significant source of processing warpage (156), and Smith (167) suggests that the use of materials that remain in the soft dough state for one to two hours may help to prevent overpacking of the mould. These long doughing properties may be achieved by the use of plasticisers or long chain methacrylate esters in the monomer; this may, however, result in bleaching (blushing or microcrazing) after some months in the mouth. Lawson (90) suggests that the working time of the dough may be extended by the use of a refrigerated dough to permit easy flow at low pressures.

It has been common practice to overfill compression moulds after the final trial pack in order to prevent the formation of bubbles. This may be achieved by failure to carry the trial packing to its
conclusion, i.e. metal to metal contact of the two halves of the flask, or by the addition of extra resin after the final trial pack. This practice is still recommended by some authors (68, 121, 136). Grunewald, Paffenbarger & Dickson (57) demonstrated that overpacking was unnecessary by removing a portion of resin from the corner of a carefully trial packed, rectangular, tin foil lined mould and processing this without the addition of any more resin. No bubbles were observed in the finished article, and although this should not be interpreted that it is not necessary to fill the mould carefully, it does indicate that there is no need for the addition of resin after the final pack.

Many authors (2, 4, 11, 57, 90, 152 & 208) feel that the main cause of "raised bite" in acrylic dentures is the use of too much force when closing the flask in the bench press. This force may cause movement of the teeth in the investment, or it may cause actual distortion of the mould itself. Anderson (4) suggests, that if pressure greater than that applied by the flask clamp is applied to the flask in the bench clamp, then separation of the halves of the flask will occur when the flask is transferred to the flask clamp. This will cause "raising of the bite". Anderson (4) also suggests that firm
closure of the flask with bolts or clamps is recommended for thin sections of resin, whilst for thicker dentures a clamp incorporating spring pressure is preferred. To be effective in compensating for the thermal expansion of the resin the spring in the clamp must not be fully compressed when the flasks have been placed in the clamp. When using this type of clamp it is important to ensure that the force used in the bench press is no greater than that which is to be applied in the spring clamp.

POLYMERISATION: The "processing" of these materials involves the application of heat and pressure to the monomer-polymer dough; thereby the monomer is polymerised to give a product which is almost entirely polymer. POLYMERISATION is the chemical reaction that occurs. The term "CURE" is used to refer to the particular combination of ambient conditions and their duration to which the dough is subjected (164). Under the conditions that are usually employed dentally, the polymerisation is relatively slow in its later stages (168) and thus a substantial minimum time is required at a particular curing temperature for a virtually complete conversion of the monomer to polymer. Hence during times shorter than this minimum time may lead to appreciable quantities
of unconverted (i.e. residual) monomer in the final hardened product. The residual monomer is one of the principal factors affecting the properties of the polymer produced with different processing cycles. The variations in physical properties are related to the degree of polymerisation, which is affected by the time, temperature, and pressure of the cure, by the presence of impurities, by the quantity of resin present and the rate of heating, (26, 63, 121, 164). There is ample evidence to show that the physical and mechanical properties of the polymer alter as the processing time is extended. For example, transverse strength, hardness, and density all increase while flexibility decreases.

**CURING conditions for the polymerisation of poly(methyl methacrylate):** It has been well established that the most suitable processing temperature for the majority of products is between 160°F and 170°F (63, 121, 200). The polymerisation reaction is exothermic (63, 121) and the degree of polymerisation attained is a function of time and the temperature within the resin. An effective curing cycle must take into account the mass and form of the sample, the ambient temperature, and the rate of temperature rise within the sample (63).
Fig. 2: Comparison of temperatures within plates of varying thickness of poly(methyl methacrylate) processed in a constant temperature water bath.

Harman (63) found that variations in curing technique did not alter the dimensional behaviour of an acrylic resin denture base provided substantial polymerisation had occurred. However, Fairhurst and Ryge (46) and other authors (136, 163, 165) found that with an extended curing time (e.g. 9 hours) at a constant lower
temperature (160°F) denture bases resulted that were
less warped than those processed with a shorter curing
time that included a period of boiling. (One hour at
160°F followed by \(\frac{1}{2}\) an hour at 212°F).

Harman (63) concluded that \(2\frac{1}{2}\) hours at a
constant temperature of 71°C (160°F) was not sufficient
time to produce substantial polymerisation in sections
3 mm. or less in thickness. Peyton (121) suggests that
for most satisfactory results most products may be placed
in a constant temperature bath at 165°F for a minimum
of four hours but preferably longer. To determine this
cycle Peyton (121) used samples that were 1" x \(\frac{1}{4}\)" x 2",
and, considering the bulk of the resin present, it is
possible that after four hours these specimens would have
been substantially cured. However, it would be unlikely
that thinner specimens (See Fig. 2) would develop sufficient
exothermic heat to enable substantial polymerisation in
this short time. Harman (63) found that thin sections
cured for nine hours or more at 71°C (160°F) conformed to
A.D.A. Specifications (184) both in deflection at the
critical loads of 4,000 and 6,000 gm. and in the maximum
load. The moderate improvement shown by extending the
cure to 48 and 72 hours could not be interpreted as an
advantage in a denture material in as much as it is
accompanied by a lack of flexibility which would make for a brittle denture.

Other authors have used specimens that could be questioned as, perhaps, being under cured. Matthews & Tyldesley (99, 100) and Johnson and Matthews (72, 73) used specimens that had been cured for six hours at 65°C (149°F) to determine the molecular weight, the tensile strength, and the fatigue resistance of acrylic resin. Tuckfield, Worner and Guerin (196) found that the thin portions of specimens cured for four hours at 66°C (150°F) had reduced stiffness and strength when compared to the thicker portions of the same specimen.

The residual monomer which results from various cures, exerts a plasticising action which weakens and softens the material. However reduction of the residual monomer to a minimum is not necessarily essential, and substantial undercuring is necessary for a pronounced reduction in the strength of the material (162, 164). Smith and Baines (161) found that the polymerisation of methyl methacrylate is never carried to absolute completion and that there is always up to 1% of residual monomer left in the acrylic resin. This small amount of residual monomer is never released except by dissolution of the
polymer itself. On the other hand short term polymerisation resulted in the appearance of further monomer which could be rapidly extracted with water. Extractable monomer in under cured denture bases was removed rapidly in water...about 17 hours in a large volume of water or in a patient's mouth (160).

Harman (63) obtained porous thick sections when the temperature of the bath was raised to 77°C (170°F). At this temperature the internal peak temperature was reached much earlier and was slightly higher than for the same sized specimen cured at 71°C. Others (121, 173) have also found this "peak" temperature and have placed it between 165°F (74°C) and 170°F (77°C). Atkinson (12) found that an increase of 3.5°C in the temperature of the bath from 62.5°C to 66°C caused a rise of more than 60°C in the maximum internal temperature inside the polymerising resin.

Although it would appear that an adequately cured denture results when a processing cycle of one to 1½ hours at about 73°C (164°F) followed by at least half an hour in boiling water (57, 72, 73, 99, 114), a longer processing time at a lower temperature is favoured by most (68, 139, 151, 165, 218). The longer cure at a lower temperature would appear to result in dentures which are more dimensionally accurate, and have less residual stress. The long cure recommended is eight to nine hours at a
constant temperature of about 73°C (164°F), (63, 173, 218).

Smith and Baines (161) recorded the length of time for the extractable monomer to be polymerised. The monomer disappearance times were:

Short cure: 1½ hours at 72°C and then 2 hours at boiling;
or
to the boil in 1 hour and then 1½ hours at boiling.

Long cure: required 12 hours at 72°C.

Ryge and Fairhurst (139) found that when identical processing cycles were used, quenching of the flask immediately after processing resulted in more warpage of denture blanks, than bench cooling the flasks for two hours before quenching. The principal factor in the lack of adaption of a denture to its cast is the rate of thermal contraction. The greater the cooling rate and the higher the curing temperature the greater the initial warpage and the residual stress. McLoughlin and Tobolsky (106) found that the properties of poly(methyl methacrylate) below the second order transition temperature were strongly dependent on the rate at which the material is cooled through the transition temperature region. When preconditioned by cooling rapidly, a sample exhibits rapid relaxation of stress upon subsequent extension. When cooled slowly before extension it shows a very much slower relaxation of stress.
On the grounds of better adaption, and reduced internal stress it was concluded (163, 165) that the lowest practical curing temperature (overnight at 72°C) was the best and that the rate of cooling from this temperature should be slow.

**DRY HEAT processing of acrylic resin:** There are now available several practices of processing compression moulded resins which eliminate the conventional water bath as a means of providing a constant temperature (121). Dry heat may be supplied by electrically heated platens, by infra-red light bulbs, or by a dry air oven. Smith (164) found that a similar result for residual monomer was obtained although a slightly slower rate of polymerisation was observed when dry heat processing methods were used. The Vernonite Work Bench (207) reported that as long as a gypsum based investment which is "full of water" is used the concept of dry heat processing was more of a fancy than a reality. As the investment is heated so is the water it contains, and so, regardless of the type of processing used, a water vapour saturated atmosphere surrounds the curing acrylic resin. Several authors have found that acrylic resin processed by dry heat methods is similar in all the properties tested to acrylic resin processed in the standard constant temperature water bath (121, 140,164,202,207).
The advantages of compression moulding as compared to the other possible methods of moulding acrylic resin to be described, are great. Compression moulding for dental appliances is simple in technique and equipment. The entire mould is available for inspection or treatment, and the properties of the appliances made by compression moulding are not inferior to those made by any other method, (136). Many authors (2, 4, 5, 86, 90, 147) have described cases of compression moulded dentures in which the vertical dimension of the dentures was opened excessively during processing. However, all of these writers have stated that this opening of the vertical dimension can be reduced by a careful technique. Shippee (147) describes the placement of escapement channels which should not exceed 5mm in width and 2 layers of baseplate wax in thickness. The resin must be condensed by careful trial closures before it is removed from the escapements. It is claimed that dentures made utilising escapements do not have any more dimensional change in the distance between the molars than do dentures cured without escapements, and, that the increase in vertical dimension is reduced by about 50%.

Bevan (15) found that the normal packing pressure of various operators was 12-14 ft.lb. and that at this pressure or slightly above considerable increase in vertical
dimension could be expected if dentures were invested in plaster. However, if dentures were invested in stone and a relatively heavy (but not excessive) packing pressure was used, then minimum opening of the vertical dimension could be expected (152). The problem of "increased vertical dimension" in compression moulded dentures would not appear to be a serious one provided a carefully controlled technique is used, and provided the dentures are invested in stone rather than in plaster of Paris.

CHAPTER 2

THE INJECTION MOULDING OF ACRYLIC RESIN: The denture is prepared and flanked in the usual manner. The mould is first incompletely filled with the prepared dough. Then the injection equipment is assembled as shown (Fig. 3) and the excess dough is placed in the reservoir. As the handle at the top is turned, the coil spring in the spring housing, exerts pressure on the piston to force the dough into the mould. The injection flask is heated in a water bath with the water covering the lower half of the flask only (57, 155, 201).
Fig. 3: (a) Pryor Injection Flask and Press  
(b) Diagrammatic cross section.

Michmann (107) claims that the injection process for acrylic denture base materials is a great improvement on previous methods. Injection techniques overcome the defect of "raised bite" but are not found to be in any way
superior to careful compression moulding (173). However, increase of vertical dimension in dentures processed by injection moulding has been reported (57) (210), and in all cases, processed by either method, there was flash to some degree. Grunewald et al (57) found that the resin in the injection press flowed only till such time as rapid polymerisation had begun. After this time there was no flow from the Pryor injection apparatus (see Fig. 3) to the main body of the resin. It is at the stage of maximum polymerisation that the main curing shrinkage occurs and it would seem probable that an appreciable amount of the curing shrinkage would be compensated for if any significant amount of resin were injected into the mould at this time. Data from the production of dentures by this technique and by compression moulding showed that this method of injection moulding dentures does not compensate for the curing shrinkage of the resin. Skinner (151) found that self-cured dentures processed by injection packing were not as dimensionally stable as those processed by the usual method of compression moulding.

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CHAPTER 3.

During recent years a number of proprietary methods of processing methyl methacrylate type materials have been introduced. These methods include:

THE VACALON PROCESS: The dentures are flaked in special flasks designed for vacuum curing. The resin used is poly(methyl methacrylate) powder and liquid without catalyst in the polymer or hydroquinone (inhibitor) in the monomer. The resin is compression packed without trial closure (219). Kafalas (76) claims that this resin contains a filler. However, Woelfel et al (219) and Paffenbarger et al (120) make no mention of the resin containing a filler. Woelfel, Paffenbarger and Sweeney (219) indicate that a specially prepared acrylic resin is recommended by the manufacturers of the special processing equipment.

Three curing cycles have been reported for Vacalon products: Woelfel et al (219) report two curing cycles used by the manufacturer, one in his laboratory, and the other at the National Bureau of Standards.

x Harold C. Emrick Laboratory, Ft. Wayne, Indiana. U.S.A.
1. The flasks were placed in the oven, which had been pre-heated to 66°C (150°F), for one hour. The oven temperature was then gradually raised to 193°C (380°F) in 2½ hours and was held at 193°C for one hour. During the heating and during cooling to 93°C (200°F) a partial vacuum (737 mm. of mercury) was maintained in the oven by a vacuum pump.

2. The flask assembly was placed in the oven at 71°C (160°F) for 1½ hours. The oven temperature was gradually raised to 138°C (280°F) in a half-hour and was held there for three-quarters of an hour. A partial vacuum of 660 mm. of mercury was maintained.

3. The third curing cycle was reported by Kafalas (76). The flasks were placed in the vacuum furnace which had been preheated to 200°F. The specimens were held at that temperature for 15 minutes under 28 inches (711.2 mm) of vacuum. The temperature of the furnace was then increased to 450°F and held for 45 minutes. At the end of this time the furnace was turned off and when the temperature had dropped to 250°F the flasks were removed for bench cooling.

Deflasking and finishing of dentures processed by this method is carried out in the usual manner.
The TILON unidirectional curing process: Uses poly(methyl methacrylate) gel with an injection moulding technique and dry heat processing (122, 139). Woelfel et al (219) and Paffenbarger et al (120) describe the Tilon resin as "copolymers of ethyl and methyl methacrylate in the form of an uncrosslinked gel". Compressed air is fed into an injector forcing Tilon gel into the mould within the flasks. The components of the flasks are made of alloys with different heat conductances so as to initiate polymerisation on the tissue side of the denture. Heat is applied only to the bottom side of the flask through the platen which is preheated to 110°C (230°F). The flasks are held at this temperature for at least 40 minutes and then bench cooled. A 'Y' shaped sprue is used for both upper and lower dentures except in cases which are very thick, when a three or four branch sprue may be necessary. Woelfel et al (219) found that the investment was bulky and hard making the deflasking operation difficult. Special equipment is needed for this process and special tin foil substitutes are recommended.

The HYDROCAST process: Uses directional hydraulic compression for the processing of compression packed dentures. Sears (145) claims that any of the present methyl methacrylate formulas can be used in this method,
while Woelfel et al (219) and Paffenbarger, Woelfel and Sweeney (120) indicate that the material is a copolymer of acrylic resins, obtained as a powder-liquid. The instrument for processing Hydrocast dentures (see Fig. 4) uses hydraulic force on the tongue side of the dentures during curing. This hydraulic force is exerted through the gypsum in the upper half of the flask and is confined to the tongue side of the dentures by a diaphragm that extends from the border of the denture to the outside of the flask. The platens are heated to 200°F prior to insertion of the flasks and are kept at this temperature for one hour. The flasks are then cooled in five minutes by circulating tap water through the manifold (219).
Fig. 4: Equipment used in processing Hydro-Cast dentures. Adjustable thermostats (T) regulate temperature of heating elements (H). Hydraulic ram (R) for closing flasks (F) is controlled by oil pump and gauge assembly (O). Water under known pressure is supplied by water-pump and gauge assembly (W) through large centre hose to water manifold (M). Hydraulic force is applied through flasking gypsum of upper half of flasks, and is directed only against tongue side of denture and a diaphragm of resin extending from border of the denture to the edge of the flasks. The two small side hoses entering the water manifold (M) are used to circulate cold water for rapidly cooling the cured dentures. Timing device is shown at (D).
CHAPTER 4

AUTO POLYMERISING or Cold-cure acrylic resins:

Over the last 20 years, probably the most significant advance in denture base materials has been the development of cold-curing acrylic resins (218). Basically these cold-cure materials are the same as the conventional heat-cured materials, that is to say they are essentially methyl methacrylate. The only difference between them is that the particle size of the polymer is much smaller and the monomer contains an additional substance, sometimes known as a "trigger" catalyst or initiator. In all acrylic resin polymers there is a percentage of a peroxide catalyst which is broken into free radicals which accelerate the polymerisation process. In the heat cured materials this breakdown of the peroxide is brought about by the heating, but in the cold-cure materials the initiator is used for this purpose (117).

Room temperature initiation; Three different initiator systems have so far been adopted for use in dental plastics (67):

1. The original method was to use a tertiary amine and an organic peroxide.

2. Toluene sulphinic acid is used but is not very stable and has an affinity for water which causes
it to deteriorate (137).

3. An initiator system using lauryl mercaptan and benzoil peroxide as initiator and catalyst had been used but not extensively.

**Amine Initiators:** Some of the resins using this initiator system are based on Schnebel's formula (82) for self polymerising resins. This formula states that the resin should contain 0.5% benzoil peroxide in the polymerised poly(methyl methacrylate) and, 0.5 to 3% n-trihexylamine in the monomer.

N-trihexylamine is a tertiary aliphatic amine. Aromatic amines may also be used as initiators, and are superior to aliphatic amines with respect to their ability to accelerate polymerisation at room temperature (133, 190) but experiments indicate that resins cured with the use of aromatic amines tend to discolor (37, 82). One aromatic amine, dimethyl-p-toluidine, will activate benzoil peroxide and does not cause a great deal of discoloration (37, 157). Replacement of half the amine content by methacrylic acid does not alter the polymerisation rate, but delays, if not eliminates the discoloration (137). The amines are liquids and are mixed with the monomer.

**Sulphinic Acid Initiators:** Sulphinic acid
derivatives as initiators are now available but are not widely used. Owing to the instability of these initiating agents, particularly in the presence of water, they were at first supplied as a third component to be mixed with each mix of monomer and polymer (37, 137). The stability of this material is now safeguarded by coating the particles of initiator with a cyclized rubber which is soluble in the monomer (102, 167). The initiator used is a toluene sulphinic acid derivative (39), and this is supplied in the polymer.

Lauryl Mercaptan Initiators: were used in some direct restorative resins. The initiator was supplied as a tablet which was added to the polymer at the time of mixing the resin (137). It would appear that this type of initiator system has not been used in prosthetic dentistry.

The Rate of Polymerisation of cold-cure acrylic Resins: In order to obtain the best results in polymerisation, the monomer:polymer:catalyst:accelerator ratio is important. The optimum ratio will vary for different accelerator-catalyst systems (22). Hedegard (67) reported that the degree of polymerisation is higher and the residual monomer content lower in rapidly rather than slowly polymerised cold-curing acrylates. Rose et al (133) found
that increased amounts of benzoil peroxide catalyst or dimethyl-p-toluine promoter shortened the time of occurrence and increased the magnitude of the peak temperatures in the polymerisation of activated polymethyl methacrylate slurries (223). From basic polymer chemistry it would appear that the increase in rate of the polymerisation reaction was due to the formation of a larger number of active centres. This would result in the formation of smaller polymer molecules. Thus, despite the fact that there would be less residual monomer to weaken a rapidly polymerised specimen it would be unlikely that a significant improvement in physical properties would be obtained because of the lower molecular weight of the polymer molecules.

Factors influencing the rate of Polymerisation:

1. As with any chemical reaction the ambient temperature is important in influencing the rate of the reaction. The temperature is also influenced by the rate of the polymerisation reaction. The reaction is exothermic (211) and, the faster the reaction proceeds the higher is the peak temperature.

2. Cornell and Powers (32) and Caul et al (29) found that with one peroxide completeness of polymerisation is proportional to the rate of polymerisation and also the concentration of peroxide.
3. Increased amounts of hydroquinone inhibitor in the monomer lengthened the time of occurrence and decreased the magnitude of the peak temperature of polymerisation (133).

4. The rate of polymerisation depends on the type of initiator and is proportional to its concentration (133).

5. Rose et al (133) found that the rate of polymerisation of cold-curing resins changed greatly with the particle size of the polymer. Fine powder speeded up the rate.

The Powder and the Liquid: Except for differences in powder-particle size, and the inclusion of the initiator, the powder and liquid are the same as normal heat-cured materials. When the powder and liquid are mixed, normally, little polymerisation occurs till heat is supplied (162). However, when self-cure powder and liquid are mixed polymerisation starts immediately. Wide variations in monomer content will occur between mixes of cold-cure resins if the temperature of mixing is not standardised. The "gelling" of the mix is accelerated by raising the temperature, and, if the temperature is raised above 70°F the saturation of the polymer particles is not always complete (82). Roydhouse (137) suggests that more monomer than the usual 1:3 ratio of monomer to polymer should be used. This results in a
more homogeneous mix, and a more fatigue-resistant acrylic with fewer regions of strain. Smith (162) reported that a slight increase in strength of heat-cured acrylic could be obtained by increasing the proportion of monomer but that this was at the expense of increased curing shrinkage. Peyton, Shiere and Delgado (123) reported that the amount of powder required for 1 cc. of liquid varied slightly, for different products, but was not significantly different from that of heat-cured resins.

The powder should be added to a measured quantity of liquid. Spatulation should be minimal as it aids in the incorporation of air bubbles, and causes monomer evaporation. Finer mesh polymers saturate and gel more quickly than coarser grade particles (82). Caul, Stanford and Serio (27) found that for the six cold-cure resins tested, the working time was shorter than that available for packing heat-cured resins, and packing and trial packing had to be done as rapidly as possible without interruption. Also a new mix of resin had to be made for each case packed. Woelfel et al (219) noted that some manufacturers recommend compression packing without trial closures. No correlation seems to exist between the powder-liquid ratio of different products and the time required to develop a suitable packing consistency. The average time for cold-cure products to
reach packing consistency was about one-third the time that is required by heat-cured products (123). Roydhouse (137) indicates that porosity of cold-cure products is often due to incomplete condensation of the material in packing. This can be overcome by packing the dough early, just before it has lost its tackiness. Some manufacturers have recommended that the flasks should be warmed slightly above room temperature before packing cold-cure products. Peyton et al (123) found that there was no increase in strength when this method was used. The practice of using a preheated flask is not recommended, since it does not appear to offer any advantage with self-curing resins; and, because there are several disadvantages related to increased rate of polymerisation and lack of adaption to the mould.

The Polymerisation of Cold-Cure Acrylic Resins:

Jeffreys (70) claims that self-processing resins can be cured in 5 to 20 minutes at room temperature. However, Skinner and Jones (151) demonstrated that a processing time of one hour at room temperature for the self-curing acrylic resin denture base materials is insufficient, as evidenced by a lack of dimensional stability for the one hour cure. The processing time should be at least two and a half hours (45). Fairhurst
and Ryge (45) found that polymerisation continued beyond two and a half hours, but Skinner and Jones (151) found that there was little to be gained so far as dimensional stability is concerned in prolonging the curing time further.

**The Degree of Polymerisation attained:** Some authors (117, 118, 190) who experimented with the earlier cold-curing resins concluded that they were undercured and were not sufficiently strong for use as a denture base material. As the temperature of polymerisation is decreased the amount of monomer converted to polymer is also decreased (28). The cold-cured resins do have a somewhat higher residual monomer content than the heat-cured resins (49, 137). Roydhouse (137) suggests that the resin should be heated at 60°C for half to one hour. This temperature is well below the transition point of the resin and should evaporate or polymerise most excess monomer in the resin.

**Curing Acrylic Under Air Pressure:** Atkinson (10) cured heat-cured acrylic under a pressure of 100 lb./sq.in. He found that thick sections of acrylic could be produced completely free of porosity and with a greatly shortened curing time. Others (54)(66)(169) have since suggested that cold-curing resins should be processed under air
pressure. A pressure of 30 p.s.i. is recommended and it has been observed by Smith, Combe and Bevan (169) and Gotfredson (54) that the polymerisation reaction is somewhat slower under air pressure and that the product is less susceptible to large air bubble inclusions. For this reason the pressure should be maintained for five to 10 minutes after the curing has been completed.
CHAPTER 5.

THE AESTHETICS AND COLOURING OF ACRYLIC RESIN DENTURE BASES.

The contouring of denture bases: Pound (124) described the reproduction of natural gingival contours in the waxing procedure in denture construction. These waxed contours (with stippling) are produced in the investment and hence in the finished denture.

Gingival contours can be coloured to closely resemble gingival tissue. Pound (124) described a technique for this, whereby coloured acrylic powders are applied to the investment in the counter-half of the flask. The colours are applied "in reverse" order and are wetted with monomer after each addition. The flasks are then compression packed in the usual manner taking care that the mould is filled, but not excessively overfilled, at the trial closure, or it is possible for the colouring material to be expressed out of the flask in the "flash". The great disadvantage of this method is that the operator is unable to see the arrangement and effect of the colouring material he has applied and must progress solely by intuition and past experience gained from the use of this method.

Johnson (75) has described a method of colouring
the flanges of dentures that is designed to overcome the major disadvantage of the technique described by Pound. A sheet of fine rubber dam is placed over the teeth in the counter half of the flask and the mould compression packed in the usual manner. After the final closure the flask is opened and the acrylic should remain attached to the model in the base of the flask. The rubber dam is removed and the stains are now applied direct to the acrylic and are wetted with monomer as above. The desired placement and intensity of stain can be applied by direct visual inspection. After the stains have been applied the flask is closed and the acrylic processed and polished in the usual manner.

In neither of these methods is it possible for the dentist to make adjustments to the labial flange of the denture without affecting the colour characterisation. This should rarely be a great disadvantage provided a carefully contoured and extended impression is taken at the impression appointment.

Powers (128) described a "brush-on" technique for the colouring of cured cross-linked plastic artificial dentures. However, the blood vessels and stippling have to be applied before processing as usual. After deflasking and pumicing, the surface to be coloured is painted with a "preparer" solution and then the coloured solutions.
The tints are prepared from a sol of monomer and mineral dyes by cross-linking with polymer solvents. Powers (128) claims that the colouring is bonded to the acrylic by the preparer solution, will not wear off, and that the acrylic base will not be crazed.

The colouring of acrylic polymer during the polymerisation of the powder has already been described (page 25). Smith (164, 166) found that the colouring material did not affect the physical properties of the cured material and also had little or no effect on polymerisation as far as residual monomer was concerned. Matthews and Tyldesley (99) found that the colouring material had no effect on the molecular weight of the cured material. Smith (166) showed that the colouring material reduced water sorption slightly. The coloured specimens gained 0.04 to 0.06% less in weight than did corresponding clear specimens. This would be regarded as insignificant.

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CHAPTER 6.

POLYSTYRENE.

Polystyrene is produced by the dehydrogenation of ethylbenzene, which is formed direct from ethylene and benzene. Various methods of polymerisation with various catalysts result in entirely different properties (127). Polystyrene is considered to consist of a mixture of long chain molecules of varied lengths. The structure most frequently proposed is a methylene chain with every other carbon atom having an attached phenyl group.

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\begin{align*}
\text{CH}_2 & \quad \text{CH} \quad \text{CH}_2 \quad \text{CH} \quad \text{CH}_2 \quad \text{CH} \quad \text{CH} \quad \\
& \quad \text{C}_6\text{H}_5 \quad \text{C}_6\text{H}_5 \quad \text{C}_6\text{H}_5 \\
\end{align*}
\]

The chemistry of the end valences has never been entirely explained. Probably they are saturated with catalyst fragments or by reactions with solvent impurity molecules, (20).

A polystyrene denture base material was developed and marketed by the Dow Chemical Company in 1950. This material, Jectron, is marketed with special equipment for its transfer injection into a dry mould (145). Woelfel et al (219) report that the investment is very hard and
subsequently deflasking is difficult.

Jectron is supplied as a precured cylindrical blank which is softened by heat and injected into the special flask. The precured rod of Jectron is heated to 210°C (410°F) in the injection cylinder which is screwed into the preheated flask. The flask assembly is bolted into the injection machine, and a screw ram engages the top of the injection cylinder. A motor drives the ram and forces the softened Jectron into the mould (219).
CHAPTER 7.

VINYL RESINS: In about 1933 vinyl type denture base materials became available in the United States of America. Of these materials Luxene 44 is essentially an 80-20 vinyl chloride-acetate copolymer resin plasticised with methyl methacrylate monomer and supplied in the form of a plastic cake or gel (49, 94, 120, 149). The material is injected into a partly filled flask in much the same way as the Pryor technique (see page 38). However, a special air gun and technique is used (163). A cross-sectional view of the equipment used in processing Luxene 44 can be seen below.

![A CROSS SECTION OF LUXENE PROCESSING EQUIPMENT]

Fig. 5: Cross sectional view of Luxene Processing Equipment.
Compressed air is fed into the air gun cylinder which drives down the piston and forces Luxene 44 gel into the mould. A single sprue is used for upper dentures, and a two or three way sprue for lower dentures. The flask is kept at 96°C (205°F) in water for 1\(\frac{1}{2}\) hours. It is then bench cooled (219).

This technique is said to eliminate change in vertical dimension and the effects of curing shrinkage. However, Grunwald et al (57) have shown that this technique does not eliminate the dimensional changes.
CHAPTER 8.

**EPOXY RESIN:**

Epoxy resin is formed by the reaction of bisphenol A with epichlorohydrin to give a low molecular weight polymer which has terminal epoxide groups (181).

The curing reaction is one of cross-linking the low molecular weight polymer which is the raw epoxy resin. The curing or setting time can be varied between one minute and many hours depending on the type of curing agent, the type of catalyst, the filler to resin ratio, and other factors. Fused quartz is the fundamental filler when epoxy resins are used as restorative materials. Other fillers are preferable when the material is used for denture base materials (21). Epoxy resins have a natural yellow or amber colour (103, 163, 167). The filler used
is usually coloured, but it is still found difficult to mask the yellow colour (103).

There are a number of agents which will accelerate or catalyse the polymerisation of epoxy resins:

1. Boron trifluoride (a Friedel Craft catalyst) and Stannic chloride will give rapid polymerisation at room temperature (21). Water acts as an inhibitor for this type of catalyst by causing its hydrolysis (105).

2. Polybasic acids, e.g. phosphoric acid, will also cause rapid polymerisation at room temperature (21).

3. Smith (159) has recently described a new curing agent, "Tung oil Trimaleate Adduct" (or TOA). The resin formed is claimed to have a low shrinkage during cure and both flexibility and toughness in the cured state. (This curing system has not as yet been tested in relation to the use of the cured resin as a denture base material.)

4. The use of dicarboxylic acid anhydrides (e.g. maleic anhydride) as curing agents is very common. This method has inherent disadvantages that limit its application. Heat is necessary to dissolve the anhydride curing agent in the resin. Heat also accelerates the curing reaction and also
volatilises some of the curing agent. The end product is of somewhat variable composition and is extremely hard and brittle (159). Some flexibility can be introduced by the addition of plasticisers. It is probable that the epoxy resin described by Vernon (198) in 1952 as "brittle when used without lamination" was cured with this type of curing agent.

5. The curing agent used in current epoxy denture base materials is probably ethylenediamine or diethylenetriamine.

The reaction is described by Bowen (21).

\[
\begin{align*}
\text{An epoxy resin} & \quad \text{(R-C-C-H)} \quad \text{Diethylenetriamine (N-R')} \\
1 & \quad \text{R-C-C-H} + \text{N-R'} \rightarrow \text{R-C-C-N-R'} \\
2 & \quad \text{R-C-C-N-R'} + \text{R-C-C-H} \rightarrow \text{R-C-C-N-R'}
\end{align*}
\]
Reaction (1) is spontaneous at room temperature. Under proper conditions, other epoxy groups then react with the newly formed hydroxyl radicles, forming the cross-linkage that gives the thermoset characteristics to the cured resin, reaction (2).

**The Method of Use of Epoxy Denture Base Material:**

1. The denture is waxed up in the usual way.

2. The denture is invested in the lower half of the flask. At this stage two or more 5/16th inch wax sprues are connected to the tuberosities, or retromolar areas, and led to the corresponding number of 5/16th inch holes that have been drilled in the back of the conventional dental flask. (Special hinged flasks are available for use with this material, however the manufacturer of Epoxolon has suggested that conventional flasks can be altered to suit. Most authors (86, 103, 219) have used this flask modification).

3. The denture is now fully invested and boiled out.

4. The mould must be thoroughly cleaned and dried. McKenzie (103) recommends that the drying be carried out at 120°F for six hours or 300°F for 45 minutes.

5. The mould is allowed to cool and two coats of the mould release recommended by the manufacturer applied.

6. The flasks are returned to the oven while the resin is prepared. The curing agent is mixed with the
tinted modified epoxy resin. (The ratio is usually 1:10 curing agent to epoxy). The resin flows readily and slowly and has the consistency of syrup before and after mixing (86).

7. The epoxy is poured into a sprue hole till it comes up through the other hole or holes.

8. The cure is now carried out. McKenzie (103) recommends a cure of $110^\circ\text{F}$ for five hours or three hours at $120^\circ\text{F}$. Other authors (7, 86) used a curing time of 120 to $125^\circ\text{F}$ overnight.

Some problems with the use of epoxys have been reported: McKenzie found that the colour was pale compared to other denture base materials, and he, with other authors (163, 167, 198, 219) have reported that there is a tendency for air bubbles to be incorporated.

Woelfel (219) found that the investment was hard and deflasking difficult. Kafalias (77) found it more difficult to obtain a high polish on epoxy specimens than on acrylic and Luxene specimens.
CHAPTER 9.

NYLON as a denture base material:

The word "nylon" had become a generic name for certain types of thermoplastic polymers belonging to the class known as polyamides. Polyamide molecules contain the amide group, CONH, spaced at intervals in a carbon chain. The polyamide molecule is thus effectively a straight chain of CH₂ groups containing the CONH grouping.

The polyamide molecule is produced in a condensation reaction between a diamine and a dibasic acid (98). First, the temperature is raised to 280°C at 250 P.S.I. in an oxygen free atmosphere, after which time the pressure is released and the mixture is heated for several hours under reduced pressure (180).

\[
\begin{align*}
H_2N(CH_2)_6NH_2 + HO_2C(CH_2)_4CO_2H & \rightarrow \\
\left[H_3N(CH_2)_6NH_3^+\right] + \left[COO(CH_2)_4CO_2\right] & \xrightarrow{\Delta} \\
\left[NH-(CH_2)_6-NH-\right] + \left[\begin{array}{c}
\overset{\scriptscriptstyle O}{\text{C}} \\
\overset{\scriptscriptstyle O}{\text{C}} \\
\overset{\scriptscriptstyle O}{\text{C}} \\
\overset{\scriptscriptstyle O}{\text{C}}
\end{array}\right] + 2H_2O
\end{align*}
\]

The number of CH₂ groups between each amide depends on the number in the original dibasic acid and
diamine. Distinction is made between the various types of polyamide by attaching a numerical prefix to the name which indicated the number of \( \text{CH}_2 \) groups in the diamine \( (y) \) and the total number of carbon atoms in the dibasic acid \( (x \neq 2) \). Ordinary or common nylon as thus become known as 6/6 or 66 nylon (above). A second type of nylon, 610 nylon, has become important for moulded articles.

610 nylon has a lower water sorption than 66 and, it is said, better dimensional stability. It is probable that this is the main reason why 610 nylon, judging by published data, is being used for denture bases. Nylon melts sharply at its melting point \( (265^\circ \text{C}) \) to a mobile liquid. This is in contrast to other thermoplastics which usually display a gradual softening over a broad temperature range to a viscous fluid. Little increase in mobility of the melt is obtained by heating nylon above its melting point. However, at 20 to 30\(^\circ\text{C} \) above its melting point oxidation of the material readily occurs, resulting in brownish markings in the denture base (98, 115).

Several authors (98, 115, 216) have each described a different apparatus for the injection of nylon into a dental mould. Each apparatus consists of a flask, the two halves of which are bolted together by at least four bolts. A tightly closed flask is necessary or the flask
would be forced open by the nylon which is very mobile when injected. The nylon is heated up in a closed container either in the injection apparatus, or in an electric oven. Careful temperature control of the heating apparatus is necessary as the melting point is sharp and the nylon should not be heated much above its melting point. Nylon is hygroscopic and if not obtained and heated in a closed container it should be dried under vacuum for four hours at 100°C. before it is used (98, 126). If the nylon is not heated in the injection apparatus, the injection cylinder should be preheated before the nylon is placed into the apparatus.

The sprue pattern does not seem to be important, as the material is very fluid and the mould fills rapidly. However, the sprue should be as short as possible as the flask, which should be preheated to 80°C is at a low temperature compared to that of the molten nylon (216).

The denture is waxed as usual, but careful waxing up and finishing is important for polishing of the finished denture is difficult. If acrylic teeth are to be used, it is necessary to provide them with strong mechanical retention (115, 216). The denture is sprued, flaked, and boiled out. Tin foil cannot be used to line
the mould as it melts when the molten nylon enters the mould (115, 216). The flask should be dried and preheated at 80°C for at least half an hour. Watt (216) found that if alginate separating medium was applied before the flask was preheated, it tended to peel off during injection. Munns (115) found that the alginate separating material tended to peel off and did not use any separating medium. If acrylic teeth are to be used the mould cannot be preheated to this temperature or surface melting will occur. It is desirable to preheat the flask for the following reasons:

1. It ensures a dry flask. Porosity in nylon dentures has been attributed to the presence of water in the flask or in the melt.

2. It ensures that all the mould cavities are filled, particularly the interdental spaces.

3. The rapid freezing of thin sections is inhibited with reduction of, and greater uniformity of, internal stresses.

4. The occurrence of flow marks is avoided (98).

The finishing of nylon dentures is similar to the method used for polymethyl methacrylate. However, it is more difficult due to the toughness of the material, and Watt (216) recommends extensive use of sandpapers of
increasing fineness before attempting to polish with whiting and wax-bound polishing agents.

Matthews and Smith (98) criticised the commercially coloured material as difficult to obtain the natural colour coupled with the translucence which is achieved in the acrylic resins. Watt (216) described two methods of colouring the uncoloured commercial material and one of these methods produced "a very natural, slightly mottled, gum pink colour in the finished dentures."

........o0o........
CHAPTER 10.

POLYCARBONATE RESINS.

Polycarbonate resins are thermoplastic materials with low water absorption and very high impact strength and toughness. A polycarbonate resin has recently become commercially available; it has good dimensional stability and can be sterilised by boiling (167). This material has not as yet been subjected to extensive laboratory tests in the dental field. However, all reports of its behaviour in the oral environment have so far been encouraging (120, 132).

Polycarbonate polymer is formed by the reaction of phosgene with bisphenol A (2,2-bis(4-hydroxyphenyl)propane) (180).

\[
\text{HO-CC-CH}_3 + \text{COCl}_2 \xrightarrow{\text{Base}} \text{CH}_3-\text{CC-CH}_3-\text{O-C}
\]

The product is a clear plastic material and is used as a moulding material usually by injection moulding.

This material is extremely sensitive to moisture contamination during heating, and injection. It is supplied
for dental use in collapsible aluminium cartridges in which it is heated and from which it is injected straight into the dental mould. Polycarbonate resin can be successfully coloured with special laquers after the prosthesis has been deflasked and polished (113).
SECTION 2

THE PROPERTIES OF DENTURE BASE RESINS

AND OF

DENTURES CONSTRUCTED OF THESE MATERIALS
CHAPTER 1.

The Tissue Acceptability of Denture Base Materials:

Obviously, before a mechanical assessment of a material is carried out to assess its possible use as a denture base material, it must have been found to be acceptable to the oral environment and the tissues therein. Accounts of allergic or toxic reactions to denture base materials or their constituents are constantly encountered (62, 119, 144, 148, 212). Any material used in the oral cavity should be extensively tested for toxic reaction (86).

A simple short-term screening method for establishing an index to the irritational qualities of materials and drugs used in dentistry has been developed (110). This test consists of subdermal implantation of pellets of dental materials in the rat; it appears that this is a satisfactory method for the study of irritancy and "tumerigenicity" of many dental materials prepared in various physical forms (58, 110, 111). Using this method, Mitchell, Shankwalker and Shazer (111) observed Wistar rats for a period of 27 months and found no evidence of tumor formation around pellets of a self-cure acrylic resin or, a heat-cured denture base resin.
Kafalias (76) studied the effects of four resins on rat connective tissues and reported a "mild" to "moderate" inflammatory reaction after 48 hour implantation. At 16 days the reaction was "mild" for all four materials, and at 32 days the reaction had diminished further except for Luxene for which a "mild-moderate" reaction was recorded.

An allergy reaction is the result of an altered reaction capacity to a specific substance which causes no symptoms of hypersensitivity in the nonsensitised subject (17). An allergy to a material can be ascertained by the use of a patch test (49, 50, 83, 212).

In many reports of allergy attributed to a denture base material, there is inadequate or no testing of the patient. Often the diagnosis of allergy was accepted due to an erythematous reaction under the whole denture strapped to the forearm for a period of 24 to 48 hours. This method of patch testing has been shown to be unreliable and the erythematous reaction, with, at times, bullous formation, has been shown to be due to a non-specific pressure effect (49, 50, 116, 119).

Most of the above authors recommend that a patch test should be carried out using scrapings of the suspect
material applied to the patient's forearm or chest. Kafalias (77) recommends that this should be done with another test as a control. The second test should use scrapings of some material, e.g. a watch band, to which the patient is known not to be allergic.

**ACRYLIC RESIN:** It has frequently been suggested that residual methyl methacrylate in the denture base arising from incomplete polymerization may be a cause of denture sore mouth (99, 161). However, it has been found (161) that water-extractible residual monomer is leached out rapidly, and that after the curing times recommended there should not be any extractable residual monomer. Axelsson and Nyquist (13) issued purposely undercured dentures to patients and observed these for a period of 1.5 to 3 years. The decrease in the residual monomer content of these dentures was observed and the only change observed in the oral mucosa was a pronounced hyperkeratosis which occurred in three-quarters of the patients. This hyperkeratosis always developed in the first week, and usually in the first 24 hours. In every patient the hyperkeratosis disappeared some time during the first month of observation.
Waerhaug and Loe (213) inserted polymerised cold-cure acrylic resin implants into extraction sockets of dogs. They found that this type of resin exerts little, if any, irritation to the periodontal tissues after 10 days or more of implantation. The cold-cure materials were found to be similar to the heat curing ones. Dachi and Laney (34) issued cold-cure acrylic resin appliances to hamsters and concluded that the absence of tissue changes after nine months indicates the unlikelihood that self-curing acrylic resin possesses carcinogenic properties for this mucous membrane.

Hedegard (67) and Nyquist (116) both issued dentures which were made of, or re-lined with, cold-cure acrylic resin and concluded that these materials were not more harmful to the mucous membrane than heat-cured acrylic resin.

Fisher (50) concludes that when acrylic resin is completely polymerised, it is no longer a sensitiser or elicitor of allergic reactions. Self-cured acrylic resin has sufficient unpolymerised monomer to give reactions in patients sensitized to the monomer. However, Smith and Baines (160) have shown that the water extractable monomer in a denture is leached out in about 17 hours.
It is therefore unlikely that even a self-cure appliance would elicit a prolonged allergy reaction, especially if it had been soaked in water prior to issue. Magnusson (97) advises that direct exposure of the skin or tissue to monomer should be avoided.

Literature on the tissue reactions to other denture base materials is sparse. No unfavourable tissue reaction to polystyrene dentures has been reported.

Kafalias (76) did not find an unfavourable tissue response to implant pellets of Luxene. No association of unfavourable tissue response to Luxene dentures has been reported. However, it must be remembered that only a small proportion of dentures are made by the Luxene and Jectron techniques and that, because the technique must be carefully controlled, there is less chance of the technique being abused with the production of an inadequate or under-cured denture (139).

The toxicity of components of EPOXY RESIN denture base materials depends on the catalyst used. Undiluted amine curing agents are caustic and can produce dermatitis by contact. The curing agent can cause irritation of the nasal mucous membranes if enough vapour is inhaled.
However, the amounts of catalyst required for dental restorations are so small as to be harmless (86, 103, 159). Kydd (85) conducted patch tests of diethylenetriamine on the forearms of 50 subjects. 18% of these subjects had positive reactions after 24 hours but did not become sensitized to the material. He concluded that diethylenetriamine is no more toxic than monomeric methyl methacrylate. The toxicity of the other component, the uncured resin, is relatively low. The oral administration of epoxy resin was tolerated without symptoms by white mice (21), and Kafalas (76) did not find an unfavourable tissue reaction around implants of the cured material in rats.

**NYLON:** No toxic effect of nylon materials has been reported (98), however, it seems likely that at least part of the surface roughness reported on nylon dentures may be due to growth of bacterial plaques (59, 216). Matthews and Smith (98) have noted that for a given masticatory stress the deformation of nylon will be higher than acrylic resin, and increased mechanical irritation of the tissues may well follow. Hallett and Farrell (59) have noted that tissue resorption did occur under a nylon partial denture that was not adequately supported by cast occlusal rests.
FLEXIBILITY OF NYLON: Flexibility is a property possessed by nylon, which is not usually considered to be advantageous in denture base materials. Watt (216) claims that full dentures made of nylon are not flexible since they are usually too thick to display this property. However, although it may be possible that upper dentures do not display a great deal of flexibility, it would be probable that a full lower denture would flex and distort around the mid-line unless it was very thick.

Storer (183) records that "in the effort to reduce the amount of denture base movement in function to a minimum it is generally recognised that a rigid denture base is desirable". Kydd (84) found that, in function, the higher the cusp angle, the greater the distortion of the denture base. However, there was not a significant difference in the distortion of the denture bases when the patient was instructed to "bite together and slide around." Lambrecht and Kydd (87) found that the contour of the palate, as well as the thickness of the denture base modified the amount of extension when the denture bases studied were loaded.

Thus, any discussion of the distortion of denture
bases must include an appraisal of the distortion in function, and, also, the angulation of the cusps used, the thickness of the base, and the depth of the palate or height of the residual ridge must be given.

The use of nylon in class 1 (Wilson) partial dentures is contra-indicated since rigid connections are desirable in order to give bracing to protect the small saddle areas from harmful lateral thrusts (216). Hallett and Farrell (59) reported a case in which cast rests and retainers were used and in which the flexibility provided the patient with comfort that he had not experienced with other dentures of rigid construction. However, Smith (163) thinks that nylon is too flexible for the majority of cases.

Watt (216) has described the flexibility of nylon as being particularly suitable for class 3 and some class 2 (Wilson classification) partial dentures since the base itself will provide for stress breaking. This should allow for some simplification of design. However Koivumaa (81) noted that, theoretically, when the saddle of the denture bends, the clasps on the teeth must shift, with the result that torque forces act on the teeth. These
torque forces act on the teeth from a lateral direction, which differs from that of the original masticatory force.

There is no literature on the tissue acceptance of polycarbonate resins. Jarby (69) found that all vital pulps in teeth in which trial polycarbonate restorations were inserted remained vital over the testing period of up to 185 days.
CHAPTER 2.

THE TESTING OF DENTURE BASE MATERIALS:

In assessing the merits of a denture base material, there are two possible yardsticks; first, the comparison of its physical properties with those of a material of proven value; and secondly, an assessment based on its clinical performance (118). Although clinical testing of dental materials is an important method of determining their usefulness (56), the general adoption of the heat-cured poly(methyl methacrylate) denture base by the profession and the patient gives a standard by which comparisons in properties of other types of resins may be made (123). However, such a comparison of different materials should be made with caution. The properties, especially mechanical, of plastics vary markedly with test conditions, preparation of test piece, and so on. In any comparison all factors must be considered; one property must not be considered singly apart from others, perhaps more important (98).

(a) The Preparation of Specimens:

The variation of conditions of preparation of moulded objects has a decided effect on the physical
properties obtained. This applies to all plastics. Thus grain size in compression moulding is important as is pressure and the processing cycle. The strains induced in extruded and injection moulded articles are different again.

An injection moulded cavity is filled by pushing material through small passages at high speeds and under pressure. Mould surfaces are relatively cold and can freeze the plastic quickly. These conditions serve to orientate the molecules in the direction of flow and to "set" the moulding before the molecules can relax and relieve the strains. It is generally found that thin mouldings appear more highly strained when viewed in polarized light, but also have enhanced strength values if tested in the direction of flow or orientation. Because of the faster rate of cooling, the strains must be greater at the surface of the moulding than at the centre. It appears that most of the strength is in the orientated surface skin. As the orientation increases the stiffness and tensile strength also increase. The higher strength is "with the grain" or in the direction of the flow. Thus one could assume that in a moulded article as for tensile strength determination, the relative strength would increase as the surface area of the specimen
increased. This is so, and the smaller the specimen the larger the strength reading obtained. (The specimen is usually an injected or extruded bar and the orientation of the molecules is in the direction in which the force will be applied in the test (20)).

Most compression moulded articles are made from granules or powder and so there is little chance for orientation. Generally compression moulded articles are weaker than injection mouldings (20). However, Smith (166) found that the surface of compression moulded specimens had a skin which was resistant to nitric acid attack. This skin was probably a homogeneous layer formed from syrup forced to the surface of the moulding. After careful wet polishing acid attack was rapid.

Boundy and Boyer (20) found that injection moulded polystyrene often has a high degree of orientation with a high longitudinal tensile strength and elongation. However, these values are quite low in the transverse direction. The material cannot distort and distribute stresses over a wide area. This lack of resilience often causes localised failures and could, perhaps, be the cause of the relatively high proportion of failure by fracture.
of Jectron dentures reported by Woelfel, Paffenbarger and Sweeney (122).

The plasticising action of water on polymers has already been described (page 13). As denture bases in service are kept in a constantly wet environment and as the mode of attack of water or water vapour varies with the rate of loading and affects crack propagation and so strength, for comparative results for different materials, only tests on fully saturated specimens under mouth conditions are of use. Even this ignores possible stress corrosive effects in the mouth (166). Various authors (23, 108, 109, 151, 166, 218) have found the time for specimens, ranging from \( \frac{1}{2} \) mm. to 6.3 mm. in thickness, to come to equilibrium with water at room or body temperature to range from 14 to 80 days. Smith (166) found that the water sorption at saturation was appreciably greater at 20\(^\circ\)C than at 37\(^\circ\)C and also agreed with the finding of Brauer and Sweeney (23) that sorption is independent of molecular weight in the 4\(^\circ\)C to 37\(^\circ\)C range.
(b) Residual Stress in Resin Structures with particular reference to acrylic resin:

The subject of "residual stress" in resin mouldings, is a large one. Stresses are incorporated into resin structures during polymerisation, during moulding, and as a result of the post moulding environment. The dimensional changes that occur during processing involve thermal changes and, also, to a lesser extent, polymerisation shrinkages in those materials the processing of which involves the polymerisation of all or part of the resin. Because the resin is contained in a comparatively rigid mould during processing, these dimensional changes are inhibited and internal stresses develop within the cured denture (191). The coefficient of thermal expansion of a gypsum mould is about 1/8th the coefficient of thermal expansion of acrylic resin. Due to the restraint of the gypsum investment caused by the interlocking mould shape, the denture is unable to shrink equally in all directions during cooling below the hardening temperature of the resin. As a result, the resin acquires strains, some of which are released when the denture is deflasked and removed from its cast. The amount of strain in a denture will depend on the shape and size of the specimen, the type of separating medium used, the rate of heat application,
the temperature range attained during polymerisation, the hardening temperature of the resin, the rate of cooling after processing, and the type of treatment during finishing and polishing (218).

When the denture is removed from its cast, some of the strain is released. This is evidenced by a change in dimension of the denture which will no longer reseat properly on to its model (172). Skinner and Jones (151) found that the processing shrinkage of dentures was greater than that obtained with denture bases without teeth. The presence of the teeth in the denture base very likely results in more complex processing stains that are later released. Horton (68) examined dentures in polarised light and found concentrations of residual stress around porcelain as well as acrylic teeth.

When a plastic object is cooled rapidly from an elevated temperature, a state of internal or residual stress is induced in the material. The stress so induced is mainly due to the thermal contraction of the plastic and to the temperature gradient which exists across the part as it cools (102). It has already been shown (pages 30-36) that the principal factor for heat-cured materials is the peak processing temperature and the rate of cooling from this temperature.
Sweeney, Brauer and Schoonover (185) and Brauer and Sweeney (23) have shown that additional stresses are produced when water can enter the polymer during curing since super-saturation may be produced on cooling. Water sorption is independent of temperature up to 60°C but begins to be very rapid as the temperature of the polymer rises from 70°C to 100°C. These observations have been supported by Fairhurst and Ryge (46) who found that dentures processed against alginate separating medium, which is permeable to water (46, 48, 205) exhibited more residual strain and hence more warpage that dentures processed against tin foil.

Paffenbarger (120) found that these internal strains were not released in service and nor were they relieved in water at a temperature in which the hand could be submerged for several minutes. However, these stress conditions are superimposed on the general pattern of stress distribution in the denture as a result of mastication or gliding movements (162).

The presence of residual stress in a resin structure may be shown by several methods:

1. Crazing tests (102, 162): The phenomenon of crazing has been defined as "fine cracks which may extend
as a network over or under the surface of, or through, a plastic." It has been observed in poly(methyl methacrylate), polystyrene, cellulose derivatives, and some vinyl polymers. The size of the cracks may vary from those visible directly to the naked eye to those which are apparent only as a haze or translucence producing scattering of light.

Internal stress is essential for crazing to occur by the use of solvents. The cracks observed are randomly orientated which follows from the postulated random orientation of the residual stresses. Any liquid which will swell or dissolve the polymer can produce this effect.

Mechanical stressing can also cause crazing. Samples craze on those surfaces which are in tension. Purely compressive forces do not produce the effect. The direction of the fissure in a mechanically crazed specimen is at right angles to the direction of the applied stress.

In general thicker test specimens seem to give a deeper more violent crazing whereas thinner samples often produce only a fine haze. A plasticised polymer exhibits lower solvent resistance than an unplasticised one, and a specimen which is both mechanically stressed
and exposed to a solvent will craze grossly (138).

Sweeney et al (185) have described a possible mechanism for solvent crazing. The transition or heat softening temperature of acrylic is between 70°C and 80°C. During processing, particularly in a high temperature curing cycle, the resin is heated above the transition temperature and the chains of the polymer are less rigidly interconnected. This allows relatively large amounts of water to be absorbed. When the resin is cooled below the transition temperature it becomes supersaturated with water. On placing the specimen in air, water and residual monomer evaporate from the surface. The shrinkage resulting from the evaporation of water and monomer from the surface causes the surface layer to be in tension. The organic solvent dissolves the polymer wherever the loss of water from the surface has created a tension or stress and the tension pulls the material apart in this region, (136). One disadvantage of this method is that stresses, on the surface of the article only, are exposed (68, 102). However, it is possible to obtain some estimation of the relative magnitude of these stresses (68).

2. Resin structures containing residual stress will distort if heated. This test is based on the assumption that all strains present will be released by the heat treatment. Horton (68) thinks that this is unlikely.
The change in shape takes place in all planes, so that any exact measurement is difficult, and standardisation for comparison of results is almost impossible.

3. Horton (68) described the use of polarised light for the detection and estimation of residual stress. As a result of his experiments, he described a special processing procedure designed to reduce the residual strain at the junction of the base material and acrylic teeth in acrylic dentures.

It should be noted that none of these methods provide any reliable indication of the magnitude of the residual stresses (102).

The effect of the mould lining on residual stress and the warpage:

Fairhurst and Ryge (46) found that the best adaption of denture blanks was obtained when tin foil was used as the lining material on both the stone model and the plaster investment. They found a slightly poorer adaption when tin foil was used on the stone model and alginate substitute was used on the rest of the mould. Skinner and Cooper (150) found that the best adaption was obtained when the cast was tin foiled regardless of how the remainder of the mould surface was treated.
Considerable warpage was found in denture blanks processed with tin foil substitute on both the stone model and plaster investment and in those processed with tin foil substitute on the stone model and tin foil on the plaster investment (46).

It is evident that the adaption of resin denture bases to the cast is improved by the use of tin foil instead of alginate as a separator (163). When tin foil substitute is used the boiling out process must be carefully carried out as the solution must be applied to clean surfaces. During the cure water may pass through the permeable alginate film and become incorporated in the polymer surface (136). Fairhurst and Ryge (45, 46) and others (163, 165, 205) have found that specimens processed against and alginate separating medium are nearly saturated with water after processing. Sweeney et al (185) found that dentures processed against tin foil lined plaster moulds did not craze, whereas dentures processed against alginate tin foil substitutes showed a strong tendency to craze.

The effect on the residual stress of the curing cycle and the rate of cooling of specimens from the polymerisation temperature has been described. The residual
stress pattern in dentures is a factor that affects service behaviour and life (166). Thus, for comparison of denture base materials, not only should the test specimens be at equilibrium with a wet environment, but, the specimens should be produced by the most common and widely used dental technique, and must be of a size that corresponds to the size of a dental moulding. In this way the effects of residual stress in the test specimens will most closely approximate the effects of residual stress on the behaviour of dental mouldings.

A realistic appraisal of the mechanical properties of denture base materials can be carried out only on the basis of the clinical requirements for the material (162). No universal agreement exists on the qualities required of the ideal denture base material or their relative order of importance, or the numerical value that should be ascribed to these qualities (98, 163). It has become apparent that the properties of plastics depend (much more so than for metals) on the speed and conditions of measurement, e.g., the ultimate strength of a bar of plastic is higher the more rapidly it is stretched. It follows from this time dependent behaviour of plastics that we can make a valid comparison for clinical use only by testing
similarly shaped pieces of material under standardised service conditions (39, 98, 163, 222).

Smith (163) and Swaney et al (184) have described tests for denture base resins and have also given numerical values for resins to equal in order to satisfy the tests. Cornell, Tucker & Powers (31) pointed out that these tests will not define a successful denture base material, but they can eliminate those with unsatisfactory properties.
(c) Strength:

Molecular weight differences only have a small effect on properties, except when a significant amount of low molecular weight material is present. The effect of residual monomer does not become serious till about 3% is exceeded. This is unlikely unless cure times less than eight hours at 70°C are employed (166).

Absorbed water seriously lowers strength and Smith (166) found that the tensile strength of saturated specimens was between 8 and 9% lower than that of dry specimens. In practice prolonged boiling may result in even lower values due to the rapid and unlimited water absorption at 100°C (23).

THE TRANSVERSE test was selected by Sweeney (186) in 1939 because it simulated the flexural loading that an upper denture receives during mastication. The optimum flexibility is unknown although in the standard tests (47) (184), flexibility and minimum transverse load limits are specified (162). Experience with this test developed refinements such as a precise method of forming the specimens and testing the water saturated specimens at body temperature and under water rather than in air.
Woelfel et al (222) found that heat curing acrylic resins had, on the average, lower strength than was reported in 1942 for similar resins (187). The average load at failure was about 700 Gm higher in the 1942 tests; however, the 1942 values are for specimens tested in air, and the values reported by Woelfel et al are for specimens tested in water after immersion for two days. (It is to be noted that:

1. these specimens would not yet, perhaps, be saturated with water (see page 87) even though these specimens were processed in alginate lined moulds.

Also:

2. Ferguson et al (48) and Fairhurst and Ryge (45) found that the transverse strength of acrylic specimens processed against alginate tin foil substitute was slightly lower than the transverse strength of specimens processed in tin foil lined moulds. This effect was most evident immediately after deflasking (48).

The transverse test for the testing of dental resins is well described by Swaney et al (184) in the American Dental Association Specification No.12 for Denture
Base Resin: (second revision). It is perhaps a pity that the conditioning of the specimens in water prior to testing is not for a longer period.

As clinically successful self-cure acrylic dentures have been made and reported by many authors (26, 27, 122, 123, 222), the deflection limits of specimens in transverse bending required in the American Specification (184) were lowered to the level of those satisfactory self-curing resins in the Federation Dentaire Internationale Specification for Denture Base Polymer (47). The cold-cure acrylic resins may fit the tissues better than most other denture bases as they have little curing shrinkage during processing. Thus a denture of this type might be flexed less in service than one processed at an elevated temperature. Peyton et al (123) concluded that there was practically no evidence to indicate that a slightly lower transverse strength results in failure in service. It may well be that the strength of these materials is just as adequate for satisfactory clinical performance as that of the heat-cured resins (117, 222).

Kimmel (80) has described an automatic shot loading machine for use in the transverse testing of dental resins. It is difficult to obtain an even flow of shot
to load the specimen when this is done by hand. The shot loading machine is claimed to overcome this difficulty and also it allows the one operator to carry out the tests and to record the deflection values.

**FLEXURAL STRENGTH:** Very little has been reported in the literature on the flexure fatigue characteristics of denture resins, although it is recognised that dentures are subjected to repeated cycles of stress during the chewing process (39, 123, 163). Smith (162) found that the predominant mode of breakage of upper dentures is by mid-line fracture during function. He has shown that this type of fracture is by flexural fatigue and come to the conclusion that the principle criterion for the functional evaluation of denture base materials is resistance to failure in flexural fatigue.

Johnson and Matthews (72, 73) used dry specimens for a fatigue strength test and found that the fatigue strength of a cross-linked (about 10% cross-linking agent) acrylic was about twice that of non-crosslinked acrylic. They also found that a cure which included a period at boiling produced non-crosslinked specimens with twice the flexural fatigue of non-crosslinked specimens that had not been boiled. However, it is to be noted that
the specimens were 1/10th of an inch thick, and that the cure which did not entail a period at boiling was for six hours at 65°C. It is likely that these specimens were under-cured and therefore plasticised by excess residual monomer.

Residual monomer and water act as plasticisers, and water also acts as a stress corrosive agent in long term tests. Smith (167) tested acrylic samples under room conditions and under mouth conditions (37°C and 100% relative humidity). He found a large drop in the resistance to flexing in the wet environment. It is likely had Matthews and Johnson (72, 73) tested their specimens in a simulated oral environment, that a very much more even value would have been obtained for crosslinked and non-crosslinked acrylic specimens. A phenomenon such as this was observed by Cornell et al (31) when they tested dry and wet crosslinked and non-crosslinked specimens for impact strength by the "falling ball test."

Peyton et al (123) tested heat-cured and self-cured acrylic samples for fatigue strength. These tests were conducted dry. No significant difference was observed between the heat-cured and the self-cured type of resin with respect to fatigue values.
THE IMPACT STRENGTH:

Failure of dentures also occurs through impact or bending -- generally outside the mouth (166).

The resistance of a denture to breaking by forces other than those exerted in chewing, such as accidental dropping of a denture during cleaning or breakage from a blow, is indicated by its impact strength (222).

There are a lot of relatively uncontrollable variables in the determination of "impact strength". The results of this type of test are more erratic than those of almost any other determination. Unfortunately the data from one set of testing conditions cannot be translated to another so that a unit value corresponding to the p.s.i. of a tensile determination is obtained. As a result impact values can be used for comparison only.

The Izod specimen test is the more usually followed. The test employs a cantilever beam which is struck by a pendulum. Notched or unnotched specimens may be used.

Temperature has little effect on impact strength below the transition stage. Cornell et al (31) found that plasticising especially by water lowered impact
strength, that crosslinking up to about 10% crosslinking agent increased impact strength.

The size and the shape of the test specimen has an unpredictable effect. It is thought that the degree of orientation and hence the method of moulding and the surface area of the specimen accounts for the differences observed. The velocity of the impacting pendulum is critical. Above about 11.5 ft/sec. an increase in the speed of the pendulum does not have much effect. A decrease in the speed produces a progressively greater impact value. Most impact tests are done with a pendulum speed of around 11 ft/sec.

Notching the specimen results in more consistent values...but the notch must be made according to standardised conditions or errors will be introduced (20).

Smith (163) has indicated that a suitable denture base material should have an impact strength corresponding to an Izod figure of 1.0 ft. lb./in. of notch. Neither the American Dental Association Specification No.12 or The Federation Dentaire Internationale specification for denture base polymers list a requirement for impact strength.
Many materials, and acrylic resin is no exception, show notch sensitivity, i.e. small notches or surface scratches and in the material, similar stress raisers are capable of reducing the strength of the part considerably (101, 136, 162). In the denture process the chance of an inclusion is sufficiently high to make this a variable and thus the ability of flaws to produce stress concentrations ought to be considered as an additional criterion when interpreting results of strength testing (166).

From the following table (Table 1) it will be observed that most denture base materials do not reach the desirable figure of 1.0 ft lb./in. of notch. However, the impact strength of polycarbonate is outstanding.
TENSILE STRENGTH: There is not a requirement for tensile strength in the American Dental Association Specification No.12 for Denture Base Resins (184) or in The Federation Dentaire International Specification for Denture Base Polymers. However, Smith (163) suggests that a denture base polymer should have a tensile strength of not less than 8,000 lb./sq.in. Matthews and Tyldesley (99) tested specimens under room conditions and reported a very low tensile value (4,600 lb./sq.in) for acrylic resin that had not been boiled during the curing cycle. Again the cycle used for these specimens was six hours at 65°C and thus the specimens are suspect of being undercured. Smith (166) found that residual monomer in excess of 3% caused a marked lowering of the tensile strength. He also reported that such a residual monomer concentration is unlikely unless cure times of less than eight hours at 70°C are used.

Smith (166) found that absorbed water seriously lowers strength. After 14 days in water at 37°C there was a reduction on the dry tensile strength of 8.9% for a dental polymer.
<table>
<thead>
<tr>
<th></th>
<th>Transverse strength grams</th>
<th>Impact strength ft/lbs in or notch</th>
<th>Flexural strength p.s.i.</th>
<th>Tensile strength p.s.i.</th>
<th>Knoop hardness</th>
<th>Rockwell hardness p.s.i.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat cured acrylic res.</td>
<td>5400</td>
<td>0.3 - 1.6</td>
<td>12000</td>
<td>5700-9200</td>
<td>13 - 21.1</td>
<td>9400 - 10400</td>
</tr>
<tr>
<td>Vacalon</td>
<td>6100</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tilon</td>
<td>6000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydrocast</td>
<td>5600</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cold-cure acrylic res.</td>
<td>3980</td>
<td>††</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polystyrene</td>
<td>6300</td>
<td>0.25-0.6</td>
<td>8000 - 5000</td>
<td>18.8-19.8</td>
<td>12400-12500</td>
<td></td>
</tr>
<tr>
<td></td>
<td>8000</td>
<td></td>
<td>19000</td>
<td>8000</td>
<td>16.7</td>
<td>10700-10800</td>
</tr>
<tr>
<td>Luxene</td>
<td>7300</td>
<td>††</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Epoxy resin</td>
<td>7000</td>
<td>0.21-0.41</td>
<td>5000 - 6800</td>
<td>16.2</td>
<td>10000-11600</td>
<td></td>
</tr>
<tr>
<td>Nylon</td>
<td>7000</td>
<td>0.5 - 1.0</td>
<td>8500 - 11500</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polycarbonate</td>
<td>14 - 18</td>
<td>11000-13000</td>
<td>9000-10000</td>
<td>11-12 (Vickers Hardness)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Matthews & Tyldesley (100) used unnotched specimens and so obtained a high reading.

†† Woelfel et al (222) found the impact strength of cold-cure acrylic resin to be slightly higher than that of heat-cured acrylic resin. Luxene was almost twice as resistant to impact as was heat-cured acrylic resin.
(d) The Effect of Strengtheners on the Strength of Denture Base Materials:

The strengthening of dentures can be carried out by three methods (91).

1. Ordinary dentures possessing high tensile strengtheners of metal or fibreglass.

2. Dentures which are basically metallic but on to which acrylic or other denture base resin is superimposed to produce a "good fit" and to retain the teeth.

3. Dentures constructed of acrylic fibreglass laminates, in which prefabricated sheets of fibreglass and acrylic are employed as integrated units.

**Type 1:** These dentures are pre-eminently resin and strengtheners are added with a view of imparting greater strength to the resin. Jennings (71) tested a variety of strengtheners. Of the four strengtheners considered only two, the lingual bar and the 0.040" stainless steel wire, significantly increased the transverse strength. The increase was in the order of 12 to 18% and as there was a wide variation in results this increase in strength may not be sufficient to produce more favourable results in practice. Similar work with a wider range of
strengtheners has been reported by Eichner (42) who found that irrespective of the type of strengtheners used or its placement, in no series of tests was the specimen superior to acrylic resin alone.

The use of glass fibre to strengthen acrylic resin does produce a pronounced increase in stiffness (167). However, there is not an increase in the tensile strength which may be reduced (163, 167) and Docking (39) reported that the increase in transverse strength was neither great nor constant.

Leader and Pearson (92) showed that when dentures were not cured at 37°C and when metal strengtheners were not placed near to or in the middle of the denture, severe warpage occurred. They concluded that metal strengtheners can be inserted in partial dentures without inducing strains or distortion when worn in the mouth, provided the cure is conducted at 37°C. No tests were conducted to establish the improvement, if any, in the mechanical properties of dentures processed at 37°C. Docking (38) and others (68, 91, 119, 162) have described "strengtheners" as "stress raisers". Stresses are readily set up in acrylic resin and its high coefficient of thermal expansion frequently contributes to this. It regards other materials as foreign
bodies and they merely act as foci of internal stress.

Regli and Gaskill (130) found that the use of metal strengtheners or metal bases reduced the distortion of lower dentures during function and deglutition from 0% to 72%. Regli and Kydd (131) reported similar results for a lower denture with a metal base. They found that the metal base denture was 8.5 times more resistant to lateral deformation than was the plastic base.

Watt (216) described the junction between teeth or metal inserts and nylon denture base materials as being a poor one.

**Type 2:** Dentures which are essentially metal: This type of denture is described by Lundquist (93). He describes the aluminium base which is cast and supposedly provides a more accurate tissue fitting surface than the normal acrylic denture. The aluminium bases, which were very thick, were more accurate than acrylic bases.

**Type 3:** Leader (91) has described a technique for the construction of dentures from acrylic fibreglass laminates. Autocryl Fibreglass and Cotton Fabric is used. This is a fibreglass that is primed to bring out good adhesion
to the resin and to maintain this adhesion. Twelve to thirty layers of this material are built up and welded together with a syrup of self-cure acrylic. A tensile strength of 25,000 to 30,000 lb./sq.in. and a flexural strength in the order of 50,000 lb./sq.in. can be obtained by this technique. This technique is slow and has not come into everyday use (167).
(e) Hardness:

Hardness can be defined as "a material's ability to withstand displacement of a portion of its surface" (209). In most types of hardness test used for dental materials, an indentor of a standard size and shape is forced into the surface of the material under test, and the material's surface displacement is then measured by optical or mechanical means. The Brinell and the Rockwell use ball type, and the Vickers and Knoop pyramid type, indenters. With the exception of the Knoop method the hardness tests named above have similar limitations. When hardness tests are conducted on brittle materials the surface shatters and the outline of the indentor is not definite. In ductile materials there is elastic recovery. In order to overcome such defects the Knoop hardness test employs a rhombic shaped indentor. When the indentation is made, a cutting action occurs along the major axis of the impression, and a spreading or indenting takes place along the minor axis. The stresses are therefore distributed in such a manner that only the dimensions of the minor axis will be subject to change by recovery. The hardness number so obtained is virtually independent of the
physical properties of the material tested (154).

Woelfel et al (222) tested specimens dry and wet. They found that Knoop values for wet specimens were lower than for dry ones. Glass-fibre-filled resins had a low Knoop number and did not hold polish well in service. However, a consistent relation of Knoop number to ability to retain polish could not be found. In this report Woelfel et al (222) have shown that hardness and abrasion resistance are not directly related and also, only small differences in Knoop numbers occur even when the denture base resins are of widely differing types. At this end of the Knoop scale a difference of about 10 units would be required for the difference to be classed as significant (76).

Woelfel et al (222) found that the Rockwell hardness of wet specimens was lower than that of dry ones. Presumably the water acts as a plasticiser. The materials least affected by immersion in water were Luxene and Jectron and those most affected were the glass-fibre-filled resins. The recovery after indentation shows the degree to which the various materials return to their original form in ten minutes. Generally the percentage recovery of wet specimens was found to be slightly less than that of dry specimens.
McCracken (102) tested self-cure materials with a Rockwell hardness tester. All four resins tested gained in hardness and in fifteen days had almost approached the hardness value for heat-cured acrylic resin. Cold-cure acrylic materials which were kept immersed in water at room temperature from the first hour on, were consistently less hard than those stored dry. However, those which were kept immersed in water at mouth temperature from the first hour had hardness values that were practically as high as those stored dry.
CHAPTER 3.

COLOUR STABILITY OF RESINS:

Both the American Dental Association and the Federation Dentaire Internationale have similar tests to ascertain whether or not a denture base resin is colour stable. Earlier authors, Caut et al. (27, 1952) and Stanford et al. (172, 1955) found that the majority of the cold-cure resins tested were not colour stable. Osborne (117) notes this fact, and attributes the discolouration to the use of tertiary aromatic or aliphatic amines as initiators.

There are now four self-cure denture base resins and three cold-cure repair resins certified by the American Dental Association as being colour stable. Other authors (30, 220, 222) have constructed dentures of these materials and found them to be colour stable.

Woelfel et al. (220) reported that dentures made with Jectron (polystyrene) showed a slightly greater tendency to collect tobacco stain than those made of poly(methyl methacrylate). This tendency was not severe enough to be a deterrent to the use of polystyrene as a denture base material.
With the exception of nylon and epoxy resin no other denture base material has been reported as not being colour stable. Woelfel et al. (29, 220, 222) and Chevitaressse et al. (30) found that clinical dentures of Epoxolon (an epoxy resin denture base material) showed a marked tendency to collect stains quickly, such as lipstick and tobacco stains. Dentures of this material showed a notable colour change usually from pink to orange. In service nylon dentures deteriorated in colour to an orange or yellow (216). Munns (115) found that about 75% of the complete nylon dentures issued had an orange discolouration after six months. This discolouration was worse when little or no oral hygiene was practiced and when the patient was a smoker. The surface of nylon dentures could not be as highly polished as could poly(methyl methacrylate), and roughening and ready adherence of deposits was found to occur after some months (115, 163, 216). Some foods and stimulants, e.g., tea and coffee, have been found to dye Prothenyl dentures, and Koivumaa (81) has suggested that the staining characteristics of nylon may be due to its high moisture absorption.
THE BONDING OF TEETH TO DENTURE BASE RESINS:
The failure of a denture base to attach itself to the teeth that are incorporated in the denture may be the result of an inherent property of the denture base material, or it may be the result of the properties of the material of which the tooth is made.

The resistance of both heat-cured and cold-cured acrylic resins to bond to acrylic teeth has been a problem in denture prosthesis (27, 102, 121). Tests have shown that it is essential that the teeth be extremely clean from wax, tin-foil substitute, or any other residue if they are to be held firmly. If the teeth have been in contact with wax they should be cleaned with kerosene-ether wax remover, or 1.5% detergent solution prior to packing the mould (123, 142). With heat-curing materials, however, there is a delay before polymerisation commences, and therefore more opportunity for a penetration of the tooth surface by monomer (3). When using a cold-curing acrylic denture base material a poor union to the teeth is obtained if a full dough of the base material is placed into the flask (27, 118). Docking (37) suggests that the acrylic
teeth should be lightly painted on the base with monomer before packing. Schoonover, Fischer, Serio and Sweeney (142) found that provided no wax or tin-foil substitute was present the tensile strength of the join of heat-cure acrylic to acrylic tooth was as high as the tensile strength of the denture base resin itself. Peyton et al. (123) have reported that the attachment of acrylic teeth to cold-cure acrylic resin may approach the attachment of acrylic teeth to heat-cured resin. However, Osborne (118) and Skinner and Jones (151) reported that the bond of self-cure materials to acrylic teeth was inadequate and that usually no union other than mechanical is expected.

Nylon does not bond chemically to acrylic teeth and so the provision of mechanical retention is just as necessary as with porcelain teeth (59, 98, 115). Matthews and Smith (98) preferred to inject the nylon denture base material into a hot mould. If this method is employed then porcelain teeth only can be used, since surface melting of acrylic teeth would occur. Acrylic resin teeth may be used, but the flask must not be preheated prior to injection.

McKenzie (103) suggests that plastic teeth
should not be used in epoxy resin dentures as there is poor adherence between them and the base material. However, porcelain teeth should be used as there is good adherence. Woelfel et al. (219) found that the expansion of clinical dentures was so great that the porcelain teeth became loosened and many replacements had to be made in the first 18 months of service.
CHAPTER 5

DENTURE BASE RETENTION:

Stanitz (174) found that the retentive force varies inversely with the fluid film thickness along the periphery of the denture. Campbell (25) found that in all the acrylic dentures tested, the retention increased after five and again after 15 days immersion in water. Some further improvement in retention was found in some cases after 85 days immersion. Stamoulis (171) found that the force used to seat a denture was proportional to and greatly influenced the force required to unseat it.

Craig, Baker and Peyton (33) found that the retention of denture bases of poly(methyl methacrylate) and polystyrene should be similar. Hamrick (60) found that the retention of heat-cured and cold-cured acrylic bases was higher than that of cast gold and cast chrome cobalt bases. He suggested that when an acrylic denture is placed in the mouth it would, because of the shrinkage that occurs during processing, displace the tissues slightly around the borders. This slight displacement is enough to decrease the film thickness in this area, thus increasing the border seal and the retention of the
denture. It is possible that the metal-base dentures were slightly oversized even though their surface detail and contour reproduction might be better than the resins. Skinner and Phillips (158) have suggested that the greater the surface area of a gold casting in relation to its volume, the less will be the casting shrinkage. Earnshaw (41) found this to be true of the chrome-cobalt alloys. In a denture base casting, the surface area:volume ratio is much greater than that of other forms of dental castings. If the same shrinkage compensation is built into the refractory investments, an over-compensation for casting shrinkage is inevitable when making a denture base casting. This might account for some of the differences in retention.
(a) MEASURING DIMENSIONAL CHANGES OF DENTURE BASES:

The necessity of having a precise replica of the tissue-bearing surface of the impression in the polished denture is unquestioned in the field of prosthodontics (218). The dimensional changes in plastic denture base materials are such that the contour of the impression surface of the denture is not a negative reproduction of the cast (95). An important criterion when selecting a denture base material is the accuracy of fit that can be obtained. None of the present denture base materials or processing methods accomplish this goal due to certain mechanical and physical properties of both the base materials and the investing compounds (93, 218). The tissues therefore have to adapt to ill-fitting bases although this warpage can usually not be detected clinically by a lack of fit (95, 170). This supposed instability of denture base resins, especially the acrylic resins, has been blamed for a number of denture failures (119).

THE MEASUREMENT OF "FIT" OR ADAPTATION:

The coefficient of thermal expansion for acrylic resin has been found to range from $73.5 \times 10^{-6}$ to
110.5 \times 10^{-6}^\circ C$, depending on whether the specimen is wet or dry, and the temperature range over which the coefficient is determined. The coefficient of thermal expansion for glass-fibre-filled acrylics is as low as $42.5 \times 10^{-6}^\circ C$, while that for Luxene and Jectron is between $61 \times 10^{-6}$ and $69.2 \times 10^{-6}^\circ C$. Thus in being heated from room temperature to $37^\circ C$, a glass-fibre-filled denture would expand about 0.07%, a Jectron denture about 0.1% and an acrylic denture up to 0.17% (35, 222). Thus it becomes apparent that if quantitative measurements are to be made, or if comparison of different materials is to be made, then measurements of dentures or denture blanks should be conducted at $37^\circ C$, or corrected to this temperature.

The possibility of teeth moving in the investment or of the mould being distorted by excessive packing pressure has been described (pages 31 and 33). It is possible that some of the change in tooth reference points, used by many authors, could be due to dimensional change of the mould, rather than actual dimensional instability of the material being tested (11).

Skinner and Jones (151) have noted that in every instance the curing shrinkage of dentures is greater than
that obtained with the denture bases without teeth. This has been found to apply to both heat-cured and self-cured acrylic dentures and is probably related to strain release. Thus it could be possible that a denture base material which is very subject to the incorporation of strain e.g., polystyrene, would exhibit a significantly greater curing shrinkage as a denture rather than as a denture base without teeth.

Some authors (93, 150) have assessed the "fit" or adaption of dentures or denture blanks by reseating them on to a master cast; and, visually, photographically, and/or by actual physical measurement, estimating and recording the lack of adaption of the posterior border of the denture to the cast. Lundquist (93) has shown that the result obtained is dependent on the force used to reseat the denture.

The most usual method of measuring the dimensional changes that occur in dentures has been to place stainless steel pins on which reference points have been marked, at various places on the denture. The placements selected by most authors (102, 114, 120, 187, 219, 220) are in the central fossa of the last molars, and in the adjacent posterior flange. The distance between these points can
be measured with a travelling microscope (219). Warpage around these points as a result of changes during processing and during service has been recorded by most of the above authors and by Fairhurst and Ryge (46). Fairhurst and Ryge (46) noted that denture blanks which were well adapted when viewed visually often had measured changes in dimension that were as great or greater than denture blanks which were obviously not well adapted. They concluded that the dimensional changes responsible for the difference in adaption of the denture blanks at different stages occur in three dimensions in such a manner that the dimensional changes recorded linearly between different measuring points across the posterior of the specimen are not representative of the total changes.

Other methods of measuring dimensional changes include:

1: The placement of gauge marks on the master cast or die. These were transferred to the acrylic baseplate and the distance between them measured (57,151).

2: The use of a pantographic type of comparator to measure the discrepancies between the tissue surface of dentures and the tissue surface of the master cast (7),
(8,122). This technique is complicated, the equipment expensive, and the results appear very similar to those obtained by other methods.

3: Giglio, Lace & Arden (53) drilled a hole through the palate of upper dentures before they were removed from the cast. Mercury was flowed through the hole and the result X-rayed. The mercury was found to flow accurately into all places where the adaption was poor. No proof was given for this last statement. This method, if accurate, would only at the best, ascertain the adaption to the cast after processing. Many authors (7, 172, 220) have recorded that the greatest dimensional change from processing becomes evident when the denture is removed from the cast and the elastic stress released.

(b) DENTURE BASES:

"Fit" has been defined as, "To conform to or cause to conform to" or "The coincidence of parts in contact" (65). Leaving aside the question or errors in the impression, which is outside the present context, there is much evidence to show that processing at the lowest practicable temperature followed by the slowest practicable rate of cooling to room temperature, produces the best initial fit and the least residual stress.
Practices which are the reverse of these constitute the principal source of processing errors (162, 165).

The stability of a denture is determined by the relationship of the denture fitting surface to the contours of the underlying tissues as compressed or displaced in function (55). Fortunately, the oral tissues show remarkable ability in adapting their contours to those of the dentures (7, 122). However it is unrealistic to expect the soft tissues to continue to cover up the changes of denture base materials in order to obtain stability and retention, but at the expense of the health of the oral tissues which must make the adaption (19, 96). In order to maintain healthy and stable oral tissues, every effort should be made by the dentist and technician to provide dentures which fit accurately and which will require the least amount of tissue change. To this extent any measurable error is important (7, 151, 165).

The residual total dimensional inaccuracy of denture base materials appears to be tolerated by the tissues. A tolerance limit does appear to exist, but bone resorption studies are needed to confirm this point (167). Woelfel and Paffenbarger (217) found that:
where changes in the dimension of the denture base occur gradually, the tissues can easily adapt and the patient does not realise that any change is taking place. Dentures of phenol-formaldehyde and epoxy resin which showed a change of dimension in the molar to molar distance of 0.75 mm. (219, 220) over twenty months of service have been described (187, 217). This change of dimension was tolerated by the patient without any apparent ill-effect. Woelfel and Paffenbarger (217) purposely warped a denture 0.94% and then 0.8% and found that the tissues made a noticeable readaptation to the new shape of the denture base within 2½ hours. However after the second warpage the denture did not seem to fit as well to the dentist.

At insertion the average dimensional change of bases ranged from 0.12 to 0.70% (220). Of course further dimensional change of these denture bases occurred after insertion, but this change was of a gradual nature. Dimensional changes of the above order could not be detected as far as fit was concerned by either the patient or the dentist (30, 120), (219, 220, 222).

Thus whilst there is evidence that relatively large dimensional inaccuracies may not apparently affect function, the highest accuracy obtainable is clearly
desirable particularly if the long term effects of an inaccurately fitting denture be borne in mind (165).
(b) **DIMENSIONAL CHANGES OCCURRING AS A RESULT OF PROCESSING:**

All the denture base resins evaluated by Anthony and Peyton (121) exhibited some degree of shrinkage as a result of processing. There was a close correlation between the degree of shrinkage and the amount of heat applied during processing. Other factors influencing the dimensional stability in a processing have been noted by Landry et al. (88):

1. The nature of the polymer.
2. The degree of cure.
3. Crosslinking density. They found that the use of a crosslinking monomer lowered the processing error and increased the stability of palate fit.
4. The presence of teeth and varying thicknesses of resin throughout the denture (151).
5. The nature of the mould sealer used.

Apparently, in the processing of dentures, a portion of the stress produced in the plastics as they cool below the second order transition point is relieved when the dentures are separated from the casts. The second order transition point is the point at which the resin changes from a rubbery to a glass-like solid. The amount of shrinkage which occurs is proportional to the
range of cooling below this temperature (7, 218).

Many authors (120, 218, 219, 221) have found that the dimensional change of thick dentures is less than that of thin dentures. This could be due to one or all of three mechanisms. It is known that the curing shrinkage of acrylic is directed towards the greatest bulk of material (36). This, in thin dentures, would possibly result in a highly stressed palatal region, and subsequent lack of fit, because the contraction would tend to be towards the bulk of acrylic that may be over the residual ridge. Woelfel et al. (221) have suggested that in thick dentures the inner material is protected from the plasticising and stressing action of water. They found that thick technic dentures showed 1/4th to 1/2 the dimensional change exhibited by the thin technic dentures. Woelfel et al. (219) also suggested that perhaps the thick dentures were rigid enough to prevent the release of some of the strain when the cured dentures were removed from the casts.

Thus, as there are many factors that vary the dimensional accuracy of denture base materials, it becomes exceedingly difficult to compare the results of different experiments by the same, or by different
authors, unless the dentures or denture bases have been constructed and measured under similar conditions.

Acrylic resin has proved itself to be rather good as a denture base and is generally accepted, although it does distort during processing and such distortion is evident clinically as an increase in the vertical dimension and in faulty adaption of the denture base to the tissues (2, 175). Atkinson (10) found that the volumetric curing shrinkage of acrylic resin doughs varied from 5% to 16% and that the average figure for experienced workers was 6.5%. The linear curing shrinkage of acrylic doughs processed in a restricting mould of the dental type has been variously measured as 0.25% to 0.55% (7), (108, 121, 156, 186, 197, 218).

None of the processing methods for acrylic resin can circumvent the acquisition of strain by a resin denture during cooling (218). In fact, Grunewald et al. (57) reported that more linear shrinkage occurred with injection processing than with ordinary compression moulding. The difference was not significant and they found that both injection and compression moulding produce equally satisfactory results.

The shape factor of the denture plus the
horizontal linear contraction tends to raise the denture from the cast in the palatal area and over the lingual ridge to a very minute degree. This adds somewhat to the vertical dimension (176). With the exception of the hydrocast technique the average increase in vertical dimension of carefully moulded acrylic dentures appears to be between $\frac{1}{2}$mm. and 1mm. measured at the pin of the articulator. This increase at the incisal guide pin becomes approximately one half this amount in the molar regions of the combined dentures when the lever ratio of the articulator is taken into account. This increase in the vertical dimension is considered to be well within an acceptable range when allowance is made for balancing the occlusion (8, 57, 219). In the case of dentures processed by the Hydrocast technique, Woelfel et al. (219) found that there was an interocclusal space between the upper and lower teeth varying from $\frac{1}{4}$ to $\frac{1}{3}$ mm. Although some of the dentures processed by the Hydrocast technique showed slight raising of the vertical dimension, the reduction of the vertical dimension in some cases is a more difficult type of error to correct than a similar error caused by an intercaptive molar or bicuspid contact.

Woelfel et al. (219) found that the adaption of dentures processed by the Hydrocast technique was as good
as the adaption of carefully moulded dentures made by the compression technique. The closing of the vertical dimension described above, was not uniform. The bicuspid, because of their smaller occlusal area, were not depressed by the hydraulic force as much as were the molars.

The four sets of Vacalon dentures tested by Woelfel et al. (219) were processed by the manufacturer. The average increase in vertical opening measured at the incisal pin, was 1.49 mm. The average shrinkage for these dentures was 0.56%. The manufacturer also processed some dentures at the National Bureau of Standards where he used a processing cycle with a lower maximum temperature. As a result of this there was a lower average curing shrinkage for these cases. The reduced curing shrinkage was 0.42%.

Tilon dentures averaged 1.29 mm. of vertical opening at the incisal pin as a result of processing changes (219). Some of this change can be attributed to movement of the bicuspid adjacent to the sprue attachment. Tilon, which is an acrylic gel, is processed at a higher than usual (278°F.) temperature. The excess heat, plus injection, may explain the higher processing shrinkage of these dentures (122).
With the cold-curing acrylic resins, less strain is acquired, hence less dimensional change and consequent better adaption to the cast is secured than with the heat-curing resins. Denture bases cured at lower temperatures will invariably fit better than those cured at high temperatures (218). Linear curing shrinkages for cold-cure specimens processed in dental moulds have been recorded as low as 0.01% (151) and as high as 0.5% (88). The higher curing shrinkages for cold-curing resins is usually obtained when the curing cycle includes a post-cure, usually in a hot air oven. The use of such a post-cure has been suggested (137) as a means of reducing the residual monomer and, increasing the strength. Recommended post-cure times range from \( \frac{1}{2} \) an hour at 72°F (108) to \( \frac{1}{2} \) an hour at 60°C (137). Landry et al. (88) found that the curing shrinkage of cold-curing acrylic resin increased with the length of the post-cure.

Since the temperature rise of the mould was small there was consequently a narrow cooling range and as a result the cold-curing plastics produced dentures with the most accurate fit (7), (70, 122). Skinner and Jones (151) processed some cold-cure acrylic dentures at 37°C and found that these dentures had a larger curing shrinkage than those processed at room temperature.
Woelfel et al. (219) recorded one case in which the vertical dimension was raised 0.75mm. This was attributed to a slight hardening of the resin before the flask could be closed.

The accuracy of the cold-cure resins is the best of all the denture base materials in common use. It is only exceeded by epoxy resin denture bases which are processed at room temperature. However the dimensional instability of the epoxy materials in service is so large as to render their suitability as a denture base material to some doubt.

Polystyrene: A systematic study of Jectron or polystyrene has not been published. The manufacturers have given the processing shrinkage as 0.2% (163). Woelfel et al. (219) found that the increase in vertical height of Jectron dentures was similar to that of Luxene dentures and similar to that of dentures made of the two brands of acrylic powder: liquid, studied. Peyton and Anthony (122) found that Jectron dentures showed a relatively high moulding shrinkage, possibly due to the high temperature (410°F) required to soften the polystyrene material for injection, and the large cooling range after hardening.
Smith (163) has noted the processing shrinkage of Luxene to be 0.2%. This shrinkage was found to be 0.27% by Chevitaese, Craig and Peyton (30). Peyton and Anthony (122) found that Luxene had a high curing shrinkage. This may be related to the tendency of the vinyl plastics to harden at a higher temperature as they cool from the softened state, even though the heat applied is not excessive 210°F.

Epoxy Resins: The curing shrinkage has been reported as 0.05% to 0.12% (30, 86, 120). In 1952 Vernon (198) expressed hope for the future of epoxy resin denture base materials as they are without curing contraction. The epoxy resin denture base materials were the most accurate tested by Paffenbarger (120) and others (30, 88) although Anthony and Peyton (7, 122) found that the epoxy resin dentures, which were cured at a slightly elevated temperature (125°F), showed a slightly higher processing shrinkage than cold-cured acrylic resin dentures, which were processed without the application of external heat. Woelfel et al. (219) found a consistently small increase in the vertical dimension of 0.33mm. measured at the incisal pin.

Matthews and Smith (98) have given the linear
mould shrinkage of Nylon as between 2.0% and 2.3%. The solidification shrinkage of the material is an inherent property, and it is thus obvious that if it is restricted stresses are set up. These stresses tend to be relieved in service due to the high water sorption of nylon (163).
(d) DIMENSIONAL CHANGES OF DENTURE BASE RESINS IN SERVICE.

The causes of dimensional change of a denture in service would be one of the following: Sorption or loss of water content of the resin base, release of strains, flexure fatigue of the base, continued curing (cold-cure resins), extreme alteration of temperature, or possibly the addition of a reliner to the denture surface (218). Unfortunately it seems impossible to avoid shrinkage during processing. However some of this is compensated by the subsequent swelling of the denture in the oral fluids (39, 109).

The sorption process may be defined as "the process in which water vapor molecules are attached to sites which may be distributed throughout the bulk phase of an amorphous or partially crystalline solid (104). All modern plastics absorb water to one degree or another, and this absorption is accompanied by a change in linear dimensions which is proportional to the change in the amount of water in the resin (61, 94, 187, 203).

Ferguson Paffenbarger and Schoonover (48) found that resin processed against tin-foil substitutes
absorbed approximately three times as much water during processing as did resin processed against tin-foil. Brauer and Sweeney (23) found that the water sorption of poly(methyl methacrylate) increased rapidly after the temperature was raised over 70°C and that the water sorption also increased when the specimens were of lower molecular weight.

Campbell (24) found that the amount of both shrinkage and expansion seemed entirely independent of the method of moulding. The expansion which accompanied the absorption of water tended to improve the retention but did not fully compensate the curing shrinkage (151). Paffenbarger et al. (120) and others (92, 151, 219) found that all the denture bases tested, with the exception of Luxene, expanded across the molar to molar measurement when they were placed in water. Ryge and Fairhurst (139) found that in general the adaption of dentures immediately after deflasking is poorer than after one month or one year of storage in water. They found that after one year's storage the adaption of acrylic resin dentures processed in tin-foil lined moulds was slightly better than the adaption of dentures processed in moulds lined with tin-foil substitute.

The expansion of acrylic resin as a result of
water sorption has been given as high as 1%. This result was obtained from an originally dry specimen. However, a newly processed acrylic resin denture is not dried out when it is deflasked, especially if a tin-foil substitute has been used as a separating medium. Normally the expansion that occurs from the sorption of water in clinical service following processing, amounts to approximately 0.3% linearly (218). Only changes so slight to be of no practical significance took place after the first three weeks immersion (24). Anthony and Peyton (7) observed dentures in water for eight months and concluded that the changes in contour of most dentures were of a minor nature (122).

Peyton and Anthony (122) found that more changes occurred in storage of Tilon dentures than with other acrylic resins. The expansion resulted in an improvement of fit which eventually approached that of the more conventionally heat-cured dentures. Ryge and Fairhurst (139) found that after one year storage in water Tilon processed in tin-foil substitute has a 0.18mm. palate space as compared to 0.06mm. space when processed in a tin-foil lined mould.

Dentures made of cold-cure acrylic showed a lower processing shrinkage than did the heat-cured materials.
(114). A certain amount of water was absorbed over a period of time and a slight amount of expansion occurred (122). McCracken (102) found that the expansion as a result of water sorption very nearly compensated for the curing shrinkage. He recorded one case of slight over-compensation. Rose, Lal, Green and Cornell (134) found the expansion of cold-cure materials in water to be 0.3\% to 0.5\% linear expansion. Hamrick (60) and Skinner and Jones (151) found that the expansion in water slightly over-compensates for the processing shrinkage and that cold-cure dentures are approximately as much oversize as the heat-cured bases were undersize. This slight over-compensation would result in a denture base which is slightly larger than the impression at the peripheries, and so would have a slightly wider fluid film at the periphery. Thus it would be expected that the retention of cold-cured dentures would be slightly lower than that of heat-cured dentures. This has been found to be so (60).

Peyton and Anthony (122) and Boundy and Boyer (20) found that the amount of water absorbed by polystyrene was so low as to have no significant effect on the mechanical and dimensional characteristics. These were the most stable plastic dentures evaluated.
Sweeney (187) found that the water sorption of acrylic-vinyl resins was very low. Although dentures of this material had a high processing shrinkage, they did not expand after storage in water as did the other plastic dentures. The low rate of water absorption is possibly related to their relative stability (78, 122, 206). Paffenbarger et al. (120) and Woelfel Paffenbarger and Sweeney (220) found that Luxene dentures shrunk 0.1% after 18 months storage in water.

All the plastic materials studied have shown some shrinkage during processing. The value for epoxy resin is less than that for any other material investigated. This very small shrinkage does not necessarily mean that the epoxy resin is superior to all others as far as the fit of the denture is concerned (30). Unfortunately it is unstable in dimension because of high water sorption. Woelfel et al. (219, 222) found that 18 month old epoxy resin dentures stored in water had expanded more than six times the curing shrinkage. At four years a lower Epoxolon denture had expanded 1.43% molar to molar and 1.19% flange to flange. Paffenbarger et al. (120) reported that the highest molar to molar expansion in any epoxy denture was about 2% after four and a half years storage in water.
Nylon: The chief drawbacks of nylons are their high processing shrinkage which causes poor adaption and warpage from the relief of processing stresses which is facilitated by the relatively high water absorption (81, 152, 163). Equilibrium under saturation conditions appears to require periods of the order of four to five weeks depending on the size of the moulding. The water sorption of 610 nylon has been given as 3% to 4%, and that of 66 nylon is considerably higher. A proportional dimensional change might be expected but, since this change is not isotropic, the expansion is unlikely to compensate for the curing shrinkage (98).
CHAPTER 7

THE REPAIR OF DENTURE BASE RESINS.

Smith (162) found that there was no connection between fracture incidence and any of the five brands of material used. However, he and others (14, 51) have found a correlation between the use of plastic posterior and the incidence of first repair. Ware and Docking (215) have advocated a polished, curved repair surface, and also the use of an acrylic cement or packing the resin at an early dough stage. Anderson (3) found that there does appear to be some advantage in repairing a denture with the same material from which it is made. The strength of the joint made with the same material was generally higher than that recorded when the joint was made with a different material. This phenomenon was also noted by Woelfel et al. (222) who found that Luxené dentures repaired with a cold-cure repair resin were weaker than the dentures repaired with the vinyl-acrylic repair resin supplied by the manufacturer.

Stanford, Burns and Paffenbarg er (172) found that the average change in dimension for dentures repaired with heat-curing resins that were boiled during the curing cycle was approximately two and a half times the change that occurred in the denture repaired with the
heat-curing resins that were heated for 8 hours at 73°C. Smith (165) showed that the maximum amount of polymerisation shrinkage which might take place in the original material on repair of a denture would not make a significant contribution to any dimensional changes. This supports the general observation (172) that the heating of the flask causes a definite strain in the high-expanding resin during confinement in the low-expanding plaster of paris mould. This strain is probably relived in the form of dimensional change. The changes that took place in the dentures repaired with the heat-cured resins were in the minus direction and Peyton and Anthony (122) found that these changes were relatively large.

Conflicting statements are made concerning the suitability of cold-cured resins for repair work. On the one hand it is perfectly true that a material polymerising at a lower temperature will eliminate the very real hazard of warpage. On the other hand it is no use preventing warpage if the repaired denture is not strong enough for normal use, and on the evidence of Stanford et al. (172) there may be good reason to suspect that this is true. However if the precautions for the handling of this type of resin as described by Caul et al. (27) and Ware and Docking (215) are followed, it is
unlikely that the union of the old acrylic material and the cold-cure resin will be insufficiently strong. Peyton and Anthony (122) found that the changes that occurred in dentures repaired with cold-cure resins were very small. Stanford et al. (172) found that the changes that did occur were in the plus direction i.e., expansion. These changes were small but approached the order of magnitude of the minus changes that occurred when a heat-cured repair material was used and cured overnight at a low temperature (73°C).

Woelfel et al. (222) found that a satisfactory repair of Epoxolon dentures could not be made using the special Epoxolon repair material and the instructions supplied by the manufacturer *. Kydd and Wykhuis (86) found that epoxy resin dentures could easily be repaired, and that the denture base shows no significant contraction or shrinkage.

* The manufacture and distribution of Epoxolon ceased nearly two years ago (43).
SECTION 3

METALLIC DENTURE BASE MATERIALS
Acrylic resin denture bases display warpage during processing and after insertion. To overcome this problem Faber (44) suggests that a cast metal base is suitable, particularly for lower dentures. Taylor (191) and Albinson (1) claim that metal denture bases accurately reproduce the detail that has been recorded in the impression without distortion or warpage. Applegate (9) records that metal based dentures are indicated where there is a serious reduction in tooth space available due to tongue enlargement, and especially in tooth borne saddles. As a rule any resorption under a metal base will be less than under a resin base because the increased thermal conductivity of the base not only allows outside thermal stimuli to reach the tissues but also allows the escape of body heat. This encourages good vascularisation of the tissues below the base.

If maximal effort is to be made to preserve the residual alveolar ridge, a cast-metal base is indicated to minimise the lateral extension of the base in function. Through such a procedure, the movement of the base over the ridge will be minimised, and a more equitable loading of the supporting tissues will be possible (87). Regli and Kydd (131) and Regli and Gaskill (130) found the use of metal bases in dentures reduced
the distortion of lower dentures in function by up to $8\frac{1}{2}$ times. They considered that deformation of the plastic base may have contributed materially to the atrophy of the alveolar ridge which was observed.

Advantages of the cast metal base (44):

1. The metal base prevents acrylic resin warpage during processing.

2. The metal base is stronger than acrylic resin, and is therefore subject to less breakage.

3. The metal base is more accurate than acrylic resin and tissue detail is reproduced more faithfully.

4. Less tissue change will occur beneath a metal base.

5. A metal base is less porous than other materials. Prolonged use leads to bacterial fermentation which along with the low thermal conductivity of the other base materials is a contributory factor to ridge resorption.

6. Metal is a better thermal conductor than acrylic resin.

7. Metal based dentures show much less lateral deformation in function.
Warpage of resin dentures has been described (page 124) however many authors (120, 219, 220) concluded that the amount of warpage that occurred in carefully processed resin dentures was far too small to have any significance practically.

That metal bases would be stronger than acrylic bases is undoubted. However Smith (167) has reported that acrylic resins are sufficiently strong for 90% to 95% of denture wearers, and that failure of a resin denture is often due to faulty handling of the resin rather than an inherent lack of strength (162, 163). The author of this review has not found a survey of the incidence of fracture of metal based dentures, or, more pertinent, of the incidence of fracture of the resin superstructure which is normally placed on metal based dentures.

Anthony and Peyton (7, 122) found that the accuracy of fit of full coverage castings of chrome-cobalt, processed at the manufacturer's laboratory, was less than expected, particularly since expanding moulds were used to compensate for the casting shrinkage of the metal. One alloy was approximately as accurate in fit as the best heat-cured dentures, and the other
brand was comparable to dentures such as Luxene and Jectron, in the special injection group.

Other disadvantages, or lack of advantage, of metal denture bases are (91):

1. Their construction is slow and costly.
2. Alterations and adjustments to metal bases are difficult and time consuming.

**Gold as a Denture Base:** The base plate is waxed with 28 gauge wax on a working cast which has been duplicated from the master cast. The working cast is poured in refractory material such as Kerr's Model Crystobalite Investment. The waxed casting is invested, cast and finished in the usual manner for dental castings (188).

Johnson (74) has noted that there is no standard for metallic denture base materials except a tentative specification issued as far back as 1928 by the United States Bureau of Standards. Johnson found that the white gold alloys tested possessed mechanical properties that were inferior to those of yellow gold; gold coloured alloys were easier to cast and were tougher. He concluded that the white gold alloys tested were not suitable as denture casting golds when given the heat
treatments recommended by the respective manufacturers. It is to be noted that Johnson used a gas-air torch to melt the alloys he used to cast the test specimens. Anderson and Bates (5) found that alloys melted in this way had an increased tendency to break in function. They found that the properties of the alloys melted in an electric induction casting machine were superior. Ryge, Kozak and Fairhurst (141) found that castings with little or no porosity were produced when the sprue diameter was larger than the thickest cross-section of the casting and was at least 9 mm. long.

**TISSUE REACTION:**

Mitchell (110) found that the reaction of rat subdermal tissue to implanted pellets of gold was minor. This was evidenced by a very thin fibrous capsule, and a scarcity of inflammatory cells. Allergy reactions to gold have been reported (194). However, this type of reaction is usually due not to the gold per se, but to other metals, particularly nickel, which have been alloyed with the gold.

**COBALT - CHROMIUM DENTURE BASES:**

The use of Cobalt-Chromium alloys in dentistry is steadily increasing, especially in the construction of
partial dentures. The composition of the various alloys varied considerably, but the basic pattern is cobalt 70\% and chromium 30\%. The cobalt which gives strength, rigidity and hardness to the alloy, may be replaced in part by nickel, resulting in a lower cost and lower melting range alloy. The alloy should contain a total of no less than 85\% by weight of chromium, cobalt and nickel. No currently known corrosion test shows adequate correlation with clinical performance. However, general clinical experience indicates that this composition requirement gives reasonable assurance of corrosion resistance (146, 192).

The cobalt-chromium dental casting alloys are usually divided into two types on the basis of the liquidus temperatures. The dividing temperature has been taken as 2,400°F on the basis that alloys melting above this temperature cannot be cast with routine success into gypsum-bonded investments (192). Earnshaw (46) found that the dental cobalt-chromium alloys were somewhat inferior in mechanical strength when compared with the typical denture casting alloys based on gold. The density of cobalt-chromium alloys is about 8.3 which is approximately half the value for denture casting gold. The ultimate tensile strength varies between 70,000 and 120,000 lbs/square inch and the hardness varies from Vickers 280 to 380.
The modulus of elasticity is much higher than for gold alloys and consequently the very low flexibility has a considerable influence on denture design. The low flexibility provides advantages when a rigid bar or plate of small cross section is required, but on the other hand it is not possible to engage as great a depth of undercut with clasps of this material as can be engaged with clasps of denture casting gold (4), 146, 189).

Anthony and Peyton (7) and Peyton and Anthony (122) found that upper cast bases of these alloys will not necessarily fit the cast better than an acrylic resin base. They found that for clinical use the lower full coverage castings appeared to fit reasonably well, but that upper castings of these alloys should be limited to the coverage of the palatal region. The possibility of the need for relining would also suggest this design. The use of cast cobalt-chromium alloy denture bases does not increase the retention of the dentures. This phenomenon has already been described (page 119) and a reason has been suggested for this result.

Morden, Lammie and Osborne (112) found that proprietary denture cleansing solutions were suitable for use on cobalt-chromium alloys provided the manufacturer's
instructions are closely followed. In the case of one proprietary denture cleaner ("Denclen") the manufacturer recommended that the denture should be wiped for one minute with a plegget of cotton wool to which some of the cleaning solution had been applied. After the denture had been wiped it should immediately be washed in water. Immersion of cobalt-chromium castings in this denture cleanser and in some household cleansers for relatively long lengths of time as would simulate regular overnight immersion, resulted in a significant loss of weight and microscopic evidence of attack.

**TISSUE REACTIONS:**

Mitchell et al. (111) implanted Vitallium, a nickel containing cobalt-chromium alloy, into the subdermal tissues of rats. In no case could any tumour formation be found over the study period of 27 months. However, extensive tumour formation was found in relation to implants of nickel and also a nickel-gallium alloy. Dermatitis as an allergy reaction to metallic alloys has been reported (143). In most of these cases the sensitivity has been attributed to the presence of nickel in the alloy.

**Stainless Steel:**

Blair and Crossland (16) have described the
history of the swaged denture base of stainless steel. They concluded that because of the number of stages involved in producing the final die and counter-die some dimensional inaccuracies can be expected. It is impossible to reproduce the fine detail obtained in the original impression because of the difficulties involved in casting the die, the relatively soft nature of the die and counter-die, with resulting damage during use, and finally the binding which takes place between the stainless steel sheet and the dies. Furthermore, because of the uneven application of pressure and the lack of clamping of the steel sheet, the thickness of the final plate is far from uniform, and local wrinkling of the sheet occurs. As a result of these difficulties it is not possible to obtain an accurate palatal fitting surface.

However austenitic stainless steel as a denture base could have many advantages:

1. Thickness can be reduced to as little as 0.004 in., whereas Paffenbarger et al. (120) have recommended that resin denture should be made as thick as possible to retain dimensional stability.

2. The thermal conductivity is such that, coupled
with the reducing thickness, temperature changes are rapidly transmitted to the sensory nerve endings of the palate. Also the quantity of heat that can be stored in the plate is small, and quickly dissipated and therefore non-irritant. Anderson and Bates (5) found that the condition of mucosa under cobalt-chromium bars and plates was better than that under any other material. The condition of the mucosa was best in those cases where the denture was worn only in the daytime.

3. Work hardened stainless steel is hard and takes a high polish. It does not corrode as easily as gold and Anderson and Bates (5) found that cobalt-chromium alloys showed better resistance to tartar deposition than either yellow or white gold.

Blair and Crossland (16) have described a high energy deformation process for the production of stainless steel base plates. The pressure wave caused by the explosion of a charge of high explosive is used to form the stainless steel plate. A die is made of an epoxy casting resin (Araldite) and the plate with an initial thickness of 0.018 to 0.008 in. is sealed across the top of a special steel pot over the die. The space between the die and the
plate is evacuated and the explosive, which is placed in plasticine on the top of the plate is detonated. It may be necessary to use more than one charge, and if so, the plate should be annealed at 1050°C for 3-4 minutes between each explosion. The authors claim that this method provides a plate of much more even thickness than a plate cast by the lost wax process by a conventionally swaged plate or by a conventional acrylic denture. They also claim that a more accurate reproduction of the palatal fitting surface is obtained. No evidence to support this claim is provided in this article.

After a base plate has been formed by this process it is necessary to spot weld cast gauze to it to provide retention for an acrylic superstructure. Also half round stainless steel wire has to be welded to the base plate to form a finishing line for the acrylic denture.

**Tissue Reaction:**

Lane (89) and Blair and Crossland (16) have found the nickel content of stainless steel to be between 7% and 8%. Allergic reaction to steel prostheses has been observed. The reported reaction consisted of discolouration of the mucosa, oedema, and eczema.
Although no specific test was conducted this reaction could well have been due to the nickel content of the alloy.
(d) **THE ALUMINIUM DENTURE BASE:**

In 1936 the development of pure aluminium had just been achieved. Prior to this date, denture bases made of aluminium had corroded badly. Campbell (25) was one of the first to describe the casting of denture bases in a purified aluminium-magnesium alloy. Lundquist (93) found that, when melted and cast electrically, this alloy which contained 3.75% magnesium, had a high resistance to tarnish and corrosion. Lundquist cast aluminium base plates which were three layers of 28 gauge wax thick. He then added two layers of baseplate wax over the castings and processed acrylic resin onto the casting by the normal compression technique. Various authors (7, 120, 218, 219) have found that thick dentures show less dimensional change than thin dentures. The dentures as tested by Lundquist above would surely rate as "very thick" and this would possibly explain the relatively high degree of dimensional accuracy that he claimed for this technique. Also no information has been published of the dimensional changes, and/or warpage, that may result in these dentures from the temperature changes to which dentures are subject in service.

Aluminium bases for dentures may be prepared by casting or by swaging. The baseplate must be flawless,
mechanically and chemically cleansed and highly polished (195). After these preparations have been carried out the base plate may be anodised for the production of an adherent, corrosion-resistant coating. Anodising is not an electro-polishing process and any scratches or flaws present are not removed but will show up more clearly after oxidation. Prior to anodising the plate should be thoroughly cleansed with benzene or carbon tetrachloride and then pickled in 10% caustic soda solution which has been heated but not above 60°C. The baseplate is rinsed in water and then pickled in 10% nitric acid and again rinsed with water.

During anodising the normal colour of the metal can be retained or the colour of the anodic film may be modified by the use of dyes. The anodising and sealing process is well described by Tregarthen (195) who, unfortunately does not detail the process of colouring the anodic film, nor does he describe to what degree an aluminium appliance can be tinted to resemble human gingival tissue.

After anodising, polishing on a lathe is not permissible, and the denture is kept clean by simply
by brushing with soap and water. Lundquist (93) found that the anodised film was pitted if aluminium dentures were soaked overnight in commercial denture cleansing solutions.
SECTION 4

DISCUSSION AND CONCLUSIONS
No denture base material in use today will accurately duplicate the impression of the tissues which form the denture area (93, 171). The whole subject of the plastic denture base is a good example of the need for a more logical and precise approach to dental materials than has been adopted in the past (162). In order to assess the value of a new material it is usual to compare its important properties in respect of the situation in which it is to be used with the corresponding properties of a tried and relatively well trusted material (98). In any comparison, one property must not be considered singly but all factors must be considered. The properties of plastics (more so than for metals) depend on the speed and conditions of measurement; also the mechanical properties of most thermoplastics decrease with increase in the ambient temperature. Thus an assessment of a denture base material must be based upon properties determined at mouth temperature and under wet conditions, and by subjecting of the material to dynamic forces (163).

Many of the results of tests on dentures and denture base materials cannot be accepted at face value because of the lack of standardisation of technique. Atkinson (11) has called for standardisation of technique
either as to the proper selection of mould material and flasks, or to a stringent control of method according to the brand, type, crushing strength and coefficient of thermal expansion of the mould material. Harman (63) found that the size of the preparation from which test specimens were cut, the method of cutting, the coolants, cutting lubricants, the types of abrasive wheels and the rate at which they turned all influenced the strength of the specimen.

Many articles lack essential data that effectively prevents the results of one author being compared with those of another. Woelfel et al. (219) and others (120, 218, 221) have found that thick dentures are about twice as dimensionally stable as are thin ones, and it is possible that this variation in dimensional stability with thickness is greater than the variations in dimensional stability between materials. Also Skinner and Jones (151) and Ryge and Fairhurst (139) and others, have shown that the dimensional behaviour of resin structures is very dependent on the heating and cooling cycle to which it is subjected, and also to the type of mould lining material employed. Some authors (57, 92, 149, 186, 187) have used steel rather than dental type moulds to produce specimens. This would produce a re-
latively unstrained specimen which would not be analogous to a structure under dental conditions and which, as a result, has a relatively high residual stress. Also many authors fail to record the material used to form the cast and the mould, or else fail to record the mould lining used. For example Campbell (24) produce acrylic base plates to test retention but failed to note the curing cycle used or the moulding lining employed. That the curing cycle, rate of cooling and mould lining affect the dimensional behaviour of denture bases has already been described. Thus the amount of dimensional change of the base plates is not known.

The American Dental Association Specification No. 12 for Denture Base Resins (184) prescribes that, prior to testing, samples should be stored in water for two days. It is unfortunate that this period is not longer. Woelfel et al. (222) found that it required three to four months in water for the high water sorption of Epoxy resins to exert the major part of its reduction of the initially relatively good properties of this material. Also Peyton et al. (123) and McCracken (102) have found that the mechanical properties of the cold-cure acrylic resin tend to improve and more nearly approach those of heat-cured acrylic if the cold-cured samples are stored in water for two to four weeks.
CONCLUSIONS

It has been shown that thick dentures are more dimensionally stable than thin ones. Also it has been shown that thicker dentures distort less in function. Anthony and Peyton (7) therefore concluded that there seemed to be some justification in the practice of adding small amounts of impression wax along the borders of impressions to improve the seal in these regions. A somewhat greater amount of thickening of the upper posterior palatal seal region and of the lingual borders of the lower dentures should be useful in achieving a more accurate fit of the finished dentures, since the largest discrepancies resulting from processing shrinkage usually occur in these regions. Matthews and Wain (101) concluded that most mid-line denture fractures begin at the lingual of the upper incisors, and are often associated with a deep incisal space. They concluded that a deep incisal space was to be avoided, and that the area lingual to the incisors should be constructed with a maximum permissible cross-sectional area, as this region is the most heavily stressed during masticatory loading. In view of these facts it would certainly seem poor practice to make a denture thinner than necessary (218).
In spite of some lack of hardness the outstanding aesthetic properties of acrylic resins have made them indispensable to modern dentistry to the extent that more than 90% of dentures made today are of acrylic resin (37, 49). The work quoted in this review has been of value to the profession inasmuch as it has led to an appreciation of the dangers of incomplete polymerisation, which has been shown to lead to deficiencies in physical properties. Consequently there should not, at the present time, be any excuse for not employing processing times and temperatures which will produce optimum properties of which the material is capable. Unfortunately it remains true that the ideal denture base material is not yet available and therefore these properties are not adequate for successful results in all types of dentures. This does not mean, however, that acrylic resins should be rejected (117). Paffenbarger et al. (120) found that none of the dimensional changes of dentures that occurred during processing or in use could be detected clinically. The conventional acrylic resins processed with the usual dental technique of compression moulding produced dentures that were just as stable in dimension as those produced by special resins and appliances. Thus it would appear that the all-round superiority of poly(methyl methacrylate) makes it the
The best current non-metallic denture base material (163).

Current opinion among recent writers (27, 122, 123, 218, 222) is that despite the fact that cold-cure acrylic resins have a slightly lower transverse strength than heat-cured acrylic resins they are resilient and tough. These qualities together with the greater dimensional stability of the cold-cure materials reported by most authors indicate that they are probably very suitable for use as denture base materials.

Grant (56) has found that the incidence of fracture of dentures made of Luxene is very much lower than the incidence of fracture of dentures made of acrylic resin. Chevita rese et al. (30) found that Luxene was the toughest material tested, however, it has been shown that the dimensional accuracy of Luxene is not as good as that of compression moulded acrylic resin.

Polystyrene or Jectron has been described as the least flexible of the plastic denture base materials. However, Woelfel et al. (219) reported that Jectron dentures were more liable to fracture than dentures of other materials. Also, probably due to the high second order transition temperature, the dimensional accuracy of dentures made of polystyrene is not as good as the
Dimensional accuracy of heat-cured acrylic resin.

The Epoxy resin denture base materials tested to date have been found to be unstable in service and to be subject to progressive and severe expansion up to 2% (120) after four years storage in water. Munns (115) has described the use of nylon for dentures for patients in psychiatric institutions. It would appear that as a result of dimensional and colour instability the only use for these materials for denture construction would be to supply "indestructible" dentures to such patients.

It has been shown (7) that cast metal denture bases are not an as accurate negative reproduction of the impression surface as had previously been supposed. Of the metals suitable for denture bases, cobalt-chromium alloys appear to be the most corrosion resistant, and the most resistant to the deposition of tartar and general debris.

As the ideal denture base material is not yet a reality, and as more synthetic resins are constantly being discovered, it behoves the dental profession to screen these materials for possible dental use. A polycarbonate resin has been described in this review.
This resin has not as yet been the subject of a laboratory or a clinical report as to its suitability as a denture base resin.

Smith (167) also mentions the possibility that a high impact polystyrene may be suitable for use as a denture base material. This type of material is an elastomer graft copolymer with styrene. It is basically similar to polystyrene and is injected moulded in the same way.


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4. Chapter 25 - 158

5. Chapter 11 - 155

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