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Creep and Sagging of Dental Alloys: A Review

Sherine Sherif Stino [1,*]

[1] Assistant lecturer, Biomaterial Department,Faculty of Dentistry, Cairo University
* Corresponding author e-mail: *sherine.stino@dentistry.cu.edu.eg*

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Abstract: Creep is defined as the permanent deformation of a material when subjected to stresses below the yield strength as a function of time and temperature. Creep is normally an undesirable phenomenon and is often a limiting factor in the lifetime of a material. Sag is the permanent deformation potential of long-span metal bridge structures at porcelain-firing temperatures under the influence of the mass of the prosthesis.

Keywords: : *Creep, sag, permanent deformation,*

Creep is defined as the permanent deformation of a material when subjected to stresses below the yield strength as a function of time and temperature. Creep is normally an undesirable phenomenon and is often a limiting factor in the lifetime of a material (1).

The temperature range in which creep deformation may occur differs in various materials. Creep deformation generally occurs when a material is stressed at a temperature near its melting point. If a metal is held at a temperature near its melting point, over a period of time at stresses well below the material's yield strength, permanent deformation can take place and the resulting strain will increase over time. The effects of creep deformation generally become noticeable at approximately 35% of the melting point for metals (2).

I. Creep test:

Creep properties of materials are determined by subjecting a heated specimen to a constant stress for long periods of time during which strain or deformation is monitored, measured, and plotted as a function of elapsed time until the sample breaks. Most of the creep tests are conducted at high temperatures, necessitating an inert gas furnace surrounding the specimen, it is usually done in a temperature-controlled room, to maintain the temperature constant and to ensure constant loading. Creep test measures the progressive rate of deformation of material at high temperature. For metals, most creep tests are conducted in uniaxial tension (3).

When the change of length of specimen (strain) is plotted versus time increments, a creep curve, is obtained, figure1. The relative increase in the elongation is referred to as the (creep) strain. The rate of deformation is called the creep rate ($d\epsilon/dt$), it is the slope of the line in a Creep strain vs. time curve. The resulting creep curve consists of three distinct stages, each of which has its own distinctive strain–time feature. A curve of creep rate versus total

strain shows the large change in creep rate during the creep test. Since the stress and temperature are constant, this variation in creep rate is the result of changes in the internal structure of the material with creep strain and time, figure 2 (2).

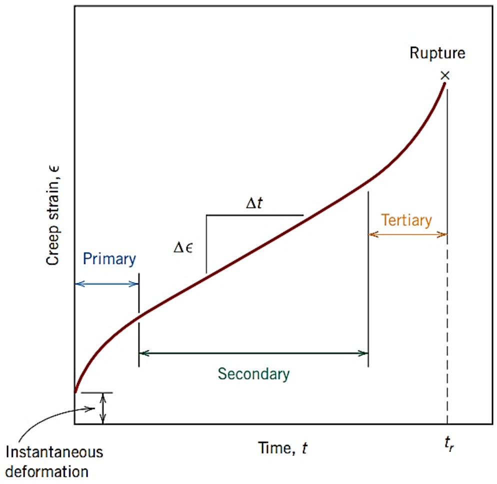


Fig.1: Typical creep curve of strain versus time at constant load and constant elevated temperature.

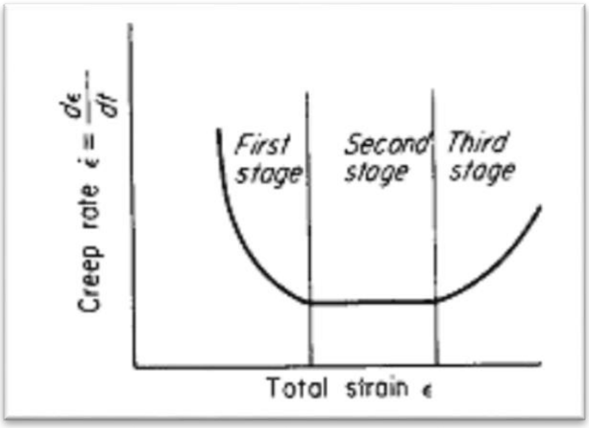


Fig.2: curve of creep rate versus total strain at constant load and constant elevated temperature.

A creep test typically shows these stages:
(i) An initial instantaneous extension or deformation.
(ii) A stage of creep at a decreasing rate.
(iii) A stage of creep at an approximately constant rate.
(iv) A stage of creep at an increasing rate ending in fracture.

Upon load application, at time t = 0, there is first an initial instantaneous deformation, rapid elongation of the specimen, that is totally elastic deformation occurring from atomic bond stretching (2).

(i) Primary or transient creep. During this stage, the strains are relatively small, deformation occurs more rapidly at first and then slows with time. It is characterized by a rapid decrease of creep rate occurring over a relatively short period time until it reaches a constant value, which corresponds to the secondary stage. In metals, this suggests that the material is experiencing strain hardening, where the metal strain-hardens to support the applied load. With further strain hardening, the deformation becomes more difficult as the material is strained and the creep rate decreases with time, the metal is experiencing an increase in creep resistance with strain (2,4).

(ii) Secondary or steady-state creep, (sometimes called linear stage). The strain increases steadily with time, it occurs relatively slow when compared to first and third stages. The creep rate is constant, it has a uniform rate. A linear relationship exists between the strain and the time. It's often the stage of creep that is of the longest duration, where most creep deformation occurs. During this stage, the constancy of creep rate is explained based on a balance between the competing processes of two opposing factors: the strain hardening that tends to reduce the creep rate and the diffusion controlled thermal recovery process (due to the higher temperature) that tends to increase it. Recovery process is slow at low temperature but is rapid at elevated temperature because high thermal energy (high temperature) enhances the atomic diffusion-controlled mechanisms as well involving highly mobile dislocations counteract the strain hardening so that the metal continues to elongate (creep) at a steady constant-state rate. Higher the rate of recovery the more is the creep deformation, and it becomes significant only at elevated temperatures. No microstructural damage nor fracture will occur at this stage (2,5).

(iii) In the final tertiary stage, it is usually observed at high stresses or/and at high temperatures. A continually increasing creep rate (rapid increase in strain with time) usually spells the beginning of the end of the specimen's test life. As this stage takes place, more and deterioration of the microstructure continues to happen until the material undergo fractures and fails completely. This failure results from microstructural changes or damages such as: grain boundary separation, the formation of internal cracks, voids growth, and, for tensile loads, necking may occur within the deformed region, figure 3. These all lead to a decrease in the effective cross-sectional area (2,6).

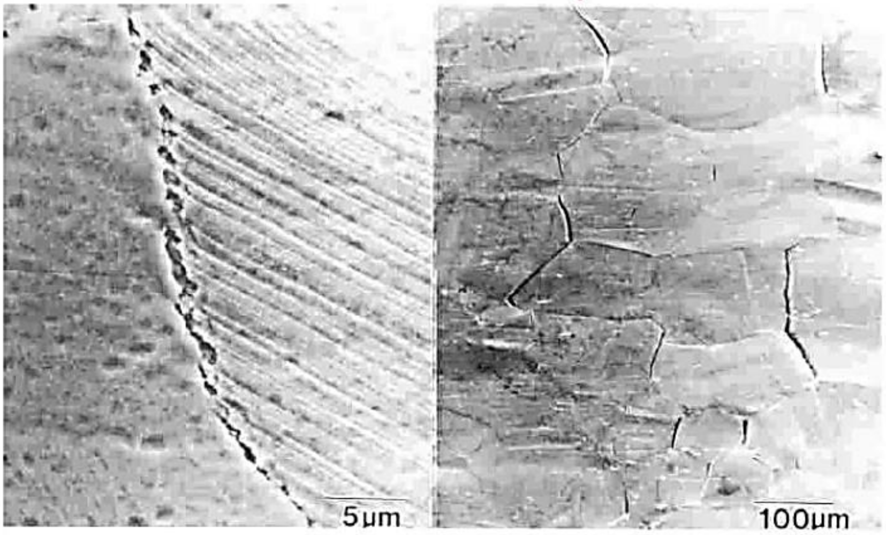


Fig.3: SEM showing voids and cracks on the grain boundary during tertiary creep stage.

II. Effect of temperature and stress on creep of metals:

Both the temperature and the level of the applied stress influence the creep characteristics. It is convenient to refer to the temperature as a function of the melting point temperature Tm on the absolute scale of temperature. Deformation generally occurs when a material is stressed at a temperature near its melting point

The effects of creep deformation of metals and alloys becomes important and generally noticeable when exposed to high temperature, at approximately 35% of the melting point (≈ 0.4 Tm), (Tm is the absolute melting temperature). When the temperature of a metal exceeds 0.4 (T > 0.4Tm), since creep is a thermally activated process, atomic diffusion becomes a significant factor and shows an exponential dependence on temperature. Therefore, the mobility of atoms or vacancies increases rapidly with temperature, atoms can diffuse through the lattice of the material. Because high thermal energy makes plastic deformation possible under lower stresses if sufficient time is provided. At a temperature substantially below 0.4Tm, the strain is virtually independent of time and creep becomes less-diffusion controlled (2,7).

Creep rate is also very sensitive to the applied stress level. At low stress and/or low temperature, some primary creep may occur but this falls to a negligible amount in the secondary stage when the creep curve becomes almost horizontal. With the increase of applied stress and / or temperature, the rate of secondary creep increases, with further increase in stress, the primary and secondary stages are shortened or even eliminated, and the tertiary creep predominates leading to inevitable catastrophic failure (2,7).

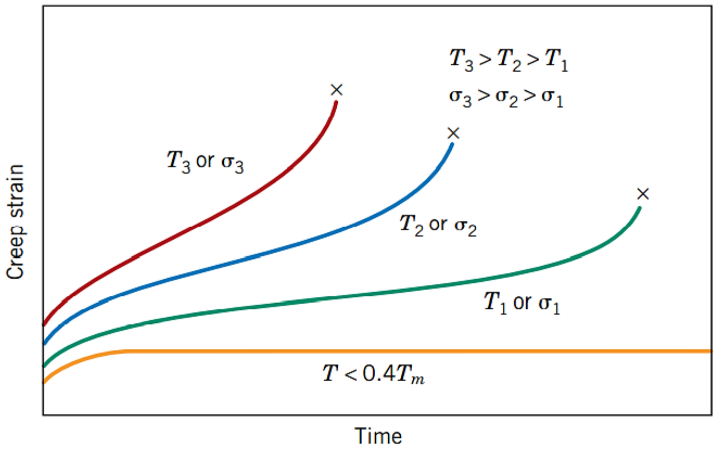


Fig.4: Effect of different stress (σ) *and temperature (T) on creep behavior.*

With either increasing stress or temperature, the following will be noted, figure4:

(1) The instantaneous strain at the time of stress application increases.
(2) The steady-state creep rate increases.
(3) The rupture lifetime decreases.

Most rate-dependent behavior in metals, such as creep is attributable to being a thermally activated process which in turn, depend on the stress, strain rate, deformation, and temperature. The strain rate at a given stress level is extremely sensitive to temperature (it goes much faster at high temperature). The higher the temperature, the more deformation and the more pronounced is the creep phenomena. Thus, creep is strongly temperature dependent, and a measurement of the temperature dependence of creep is important (6,8).

The rate at which deformation proceeds is described by an Arrhenius rate law equation:

$\epsilon = A_o \exp(-Q / RT)$

ϵ is steady-state creep rate or the tensile strain rate.
A_o is constant proportional to number of dislocations.
Q is the activation energy for dislocation motion (to free from obstacles).
R is gas constant and T is absolute temperature in Kelvin.

III.Mechanisms of creep in metals:

Creep deformation involves mechanisms at the atomic scale. Depending on the temperature range and the stress level, several theoretical mechanisms have been proposed to explain the different creep behavior of crystalline materials, these include (9):

1-Diffusional creep.
2-Dislocation creep that involves dislocation glide and climb.
3. Grain-boundary sliding.

1.**Diffusional creep**:

Diffusion creep represents a creep process controlled by diffusion of atoms or vacancies in the material, under low applied stress, where stresses not high enough to move dislocations (as the crystal resistance almost inhibits dislocation motion) but enough to help atomic diffusion by passive movement of atoms from higher concentration to lower concentration till equilibrium is the key mechanism for this type of creep deformation (5,10).

At low stress a high temperature is needed to cause a measurable creep rate, when the temperature range T > 0.4Tm, creep can be divided into two major groups, depending on the path of diffusion of vacancies: **boundary mechanisms**, in which grain boundaries diffusion takes place at moderately elevated temperatures (Coble creep) and **lattice mechanisms,** at high temperatures diffusion through the lattice becomes dominant and more rapid, so bulk diffusion takes place (Nabrro-Herring creep), figure 5 (5,10).

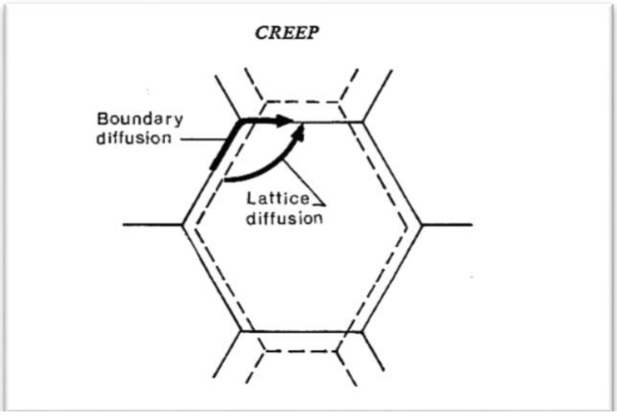


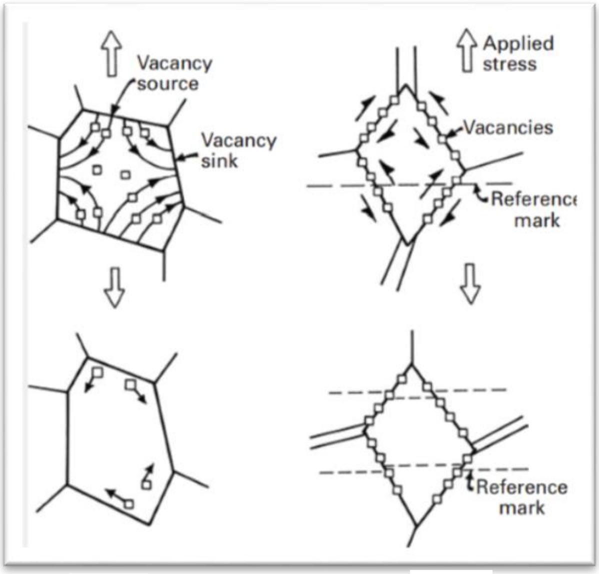
Fig.5: Diffusion Paths in a strained crystal at elevated temperature.

1.1. Nabarro-Herring creep

When a low stress is applied on a polycrystalline material at high temperature, diffusion of vacancies and atoms takes place through the crystal itself, the grain interiors by bulk diffusion because the energy needed for vacancy diffusion within the lattice is typically larger than that along the grain boundaries. As a tensile stress is applied to grain boundaries, the grain boundaries that are perpendicular to the stress, are in tension, distended, while the grain boundaries that are close to parallel to the tensile stress are in compression. Diffusion creep rate is a linear function of the applied stress, so stress alters the atomic volume in these regions; it is increased in regions experiencing a tensile stress and decreased in the volume under compression. Vacancies diffuse from grain boundaries that are under tensile stress (higher vacancy concentration) towards grain boundaries under compressive stress (lower vacancy concentration). Vacancy diffusion passes through the grain itself, where atoms can be considered to flow in the opposite direction. The atomic diffusion leads to elongation of the grains in the tensile direction, figure 6 (10).

1.2.Coble creep

Coble creep is based on diffusion along the grain boundaries instead of in the bulk. At low or moderately elevated temperature and low stress, the main diffusion path is via grain boundaries, because the energy needed for grain boundary diffusion is significantly lower than for diffusion through the bulk of the crystal and the cross-sectional area available for diffusion along grain boundaries is much less. Grain boundaries represent “easy paths” for diffusion since atoms at grain boundaries are less closely packed, disordered than in a perfect lattice, diffusion of atoms or vacancies is more rapid and easier through the porous grain boundaries. The atomic diffusion in the lattice becomes progressively more difficult and slows down relative to grain boundary diffusion with decreasing temperature, figure 6 (9,10).



(a) (b)

Fig.6: Flow of vacancies according to (a) Nabarro-Herring c and (b) Coble mechanisms resulting in an increase in the length of the specimen.

2.Dislocation creep:

Dislocation creep is a deformation mechanism in crystalline materials, which involves the movement of dislocations through the crystal lattice of the material causing plastic deformation. It is the dominant deformation mechanism in most crystalline materials. Dislocation creep occurs through dislocation glide and dislocation climb (12).

2.1.Dislocation glide:

Dislocation gliding is the normal plastic deformation movement along the slip planes. In metals, it involves motion of dislocation which is controlled by glide at low temperatures and does not depend on diffusion. Dislocation motion may be stopped and obstructed by obstacles on its slip plane, such as other dislocations, precipitates, grain boundaries which exert forces on a dislocation as it moves on its slip plan and increases the resistance to dislocation movement. Any form of obstacle used for blocking dislocations would then reduce creep deformation. At low applied stress, dislocations are unable to bow around or cut through the obstacle. it's not enough for moving dislocation to overcome the obstacle via dislocation slip alone (9,10).

2.2 Dislocation climb:

At elevated temperatures, the increased energy permits dislocations in a metallic material to climb to a different plane. In climb, the atoms gain energy, so atoms move either to or from the dislocation line by diffusion (diffusion of vacancies or interstitial atoms through a crystal lattice), causing the dislocation to move in a direction that is perpendicular to the direction of slip plane. The dislocation, then escapes from lattice imperfections and overcome those obstacles, continues to slip, glide on the new plane, causing additional deformation of the specimen even at low applied stresses, figure 7 (9,10).

This process repeats itself each time when the dislocation glides, along new slip plane until it encounters another resisting obstacle, in which atoms move out of the slip plane, then the dislocation again climbs up or down to another slip plane and the process is repeated**.** Thus, dislocation creep involves the sequential processes of dislocation glide coupled with dislocation climb that assists to overcome barriers by a process of diffusion motion of vacancies(10,11).

Dislocation gliding produces almost all the creep strain, which is much faster than dislocation climb that controls the creep rate (how rapidly the dislocations can overcome obstacles that obstruct their motion by the slower atomic diffusion and mobility of vacancy) (12).

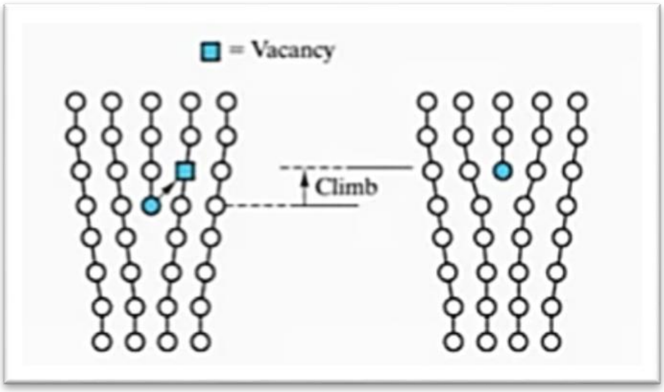


Fig.7: Dislocations can climb when atoms leave the dislocation line to fill vacancies.

3.Grain boundary sliding (GBS):

The onset of tertiary creep stage is a sign that structural damage has occurred in an alloy. when occurring at sufficiently high temperature, grain-boundary sliding usually plays an important role in this stage. Large amounts of grain boundary sliding may occur, under the action of shear stresses acting on the boundaries, causing the movement of grains relative to each other and leading to initiation and propagation of inter-crystalline cracks, voids formation, and ultimately fracture (9,10).

Grain-boundary sliding does not represent an independent deformation mechanism. The sliding of the grain boundaries, under the influence of the applied shear stress, and diffusional creep can be considered to take place sequentially in the individual grain. Diffusional creep leads to grain separation, which is followed by grain-boundary sliding causing to 'heal' voids between grain, that would otherwise open up due to grain boundary diffusion. To maintain grain continuity and prevent the formation of internal voids or cracks during diffusional process, the grain-boundary sliding rate must exactly balance the diffusional creep rate, figure 8 (9,10).

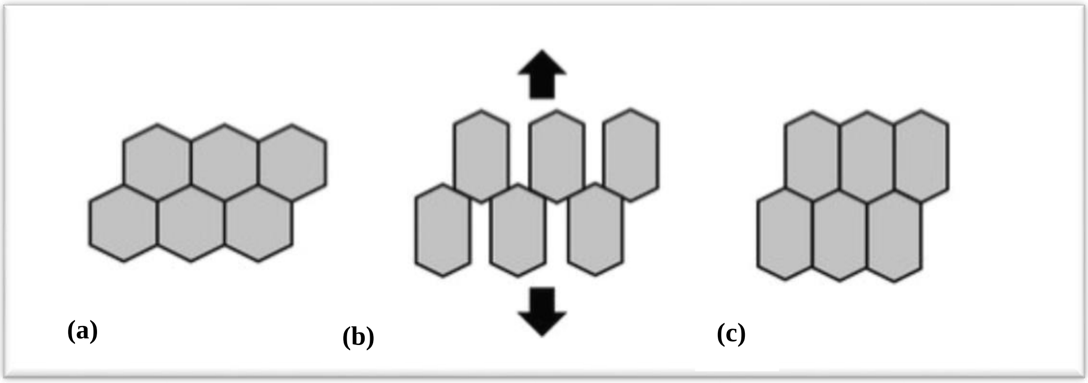


Fig.8:

a) Initial configuration of six grains before creep deformation

b) Following diffusional creep, under tensile load applied, one dimension of the grains is increased and the other decreased creating gaps, voids between the grains.

IV.Effect of grain size on creep of metals:

Several factors affect the creep characteristics of metals. These include melting temperature, elastic modulus, and grain size. In general, the higher the melting temperature. The higher the metal exposed to high temperatures, the larger or coarser the grain size, the better a material's resistance to creep than refined grains so that the fracture time increases giving it an advantage over the creep properties of metals (2,10).

The effect of grain size on secondary or steady-state creep rate has been studied to a great extent. The creep mechanism of metals can occur in grain boundary sliding (GBS), diffusion creep (Nabarro–Hearring diffusion creep and Coble creep), and dislocation creep. The mechanism is theoretically equally influenced by grain size that steady-state creep rate increases with increasing grain diameter (13).

The grain size of polycrystalline metals is important since the amount of grain boundary surface has a significant effect on many properties of metals, especially strength. Grain boundaries at lower temperatures usually strengthen polycrystalline metals by providing barriers to dislocation movement. A fine-grained material is harder and stronger than one that is coarse grained because the former has a greater total grain boundary area to impede, stop dislocation motion. However, during creep deformation at elevated temperatures, grain boundary sliding may occur, and the grain boundaries become regions of weakness (grains shear relative to each other at grain boundaries, where large amount of strain is believed to be accumulated by the sliding of individual grains relative to each other). The contribution of grain-boundary sliding to plastic deformation is more significant the greater the grain boundary surface per unit volume. Since the grain-boundary surface is inversely proportional to the grain size, fine-grained material permits more grain boundary sliding, resulting in higher creep rates than in materials with coarse grain sizes (13,14).

Also, the grain size plays a major role in diffusional creep, where creep rates increase linearly with the stress and inversely with the square of grain size. As grain size decreases, the area of the grain boundaries increases, the creep rate increases, the length of the diffusion path is smaller, and diffusion is faster than for coarser-grained ones. A practical way of having an alloy with high resistance to Nabarro-Herring or Coble creep is to increase the size of the grains, by coarse grains. As well creep resistance is improved if diffusion rates are reduced, diffusion is lower as well in materials with high melting point (5).

High-temperature creep is dependent on dislocation climb, the creep rate increases with increase in the rate of diffusion of vacancy to the dislocation. Vacancy can diffuse more rapidly along high-energy grain boundaries than through the interior of the grains. Vacancy diffusion is rapid in a fine-grain-size material having a greater number of grain boundaries and so, the creep rate is higher. While material with coarser grain will have lesser grain boundary areas for which vacancy diffusion is relatively slow, the material will result in a lower creep rate and higher resistance to creep (5).

Creep rates are also reduced by utilizing materials with high elastic modulus, the greater the elastic modulus (the greater the stiffness of the material which depends on the strength of the bond), the less is the strain rate. Thus, the dislocation creep barriers or obstacles in higher elastic moduli materials take longer time to overcome and thereby the slower creep rates and the better the creep resistance (13).

V. Dental examples of creep:

Dental amalgam is a good example of a material showing creep behavior. Creep of amalgam is dependent on the yield strength of the material and the temperature of the environment. It only becomes a serious problem when the environmental temperature is greater than half the melting temperature, where the amalgam phases have very low melting temperatures, slightly above the room temperature (about 80°C). As well when the restorations are subjected to stresses of mastication, which are usually well below the normal static yield strength, and for an extended period. Creep will be occurring and produce continuing plastic deformation of the restoration, the process can, over time, be very destructive to a dental amalgam filling causing the amalgam to extend out of the restoration site, increasing its susceptibility to marginal breakdown (15).

Low-copper dental amalgam with mercury-based phases, silver-mercury $\gamma1(Ag2Hg3)$ and tin-mercury $\gamma2$ (Sn8Hg) phases are most prone to creep. When an amalgam creeps, it is $\gamma1$ phase that deforms plastically, it has a big effect on creep rates and $\gamma2$ phase increases the creep rate. The mechanism of creep in dental amalgam is grain boundary sliding, where the presence of $\gamma2$ phase at the grain boundaries accommodates the sliding of the $\gamma1$ grains, giving rise to higher creep values. Increased creep rate is shown by larger $\gamma1$ volume fractions, decreased creep rate is shown by larger $\gamma1$ grain sizes. Thus, for a given load at a given time, the low-copper amalgam has a greater strain (1,16).

High-copper amalgam have lower creep values prevailing because γ2 phase has been eliminated and copper-tin η (Cu6Sn5) crystals act as barriers to deformation on γ1 grains blocking grain boundary sliding of γ1 and therefore are responsible for decreased creep values of high copper alloys (1,16).

Low-copper amalgam shows greater strain, and higher amount of creep than high copper amalgam, figure 9. The clinical importance, is the greater creep in low-copper amalgam results in more amalgam protrudes at the margin of the restoration and greater marginal overhanging and fracture, leaving a ditched amalgam around the margin which can lead to secondary decay. This contributed to its decline in popularity, low-copper amalgam is no longer commonly used in dentistry. While the absence of the corrosion-susceptible γ2 phase in the microstructure of high-copper amalgams is assumed to be the principal factor responsible for the superior resistance of these alloys to marginal breakdown. A correlation between creep and marginal breakdown exists, where amalgam alloys having creep values below 1%, were free of γ2 phase and show differences in clinical performance. Whereas amalgam having creep values higher than 1%, were found to contain γ2 shows marginal breakdown (16).

Thus, the primary importance of creep is to determine the presence and absence of tin-mercury (γ2) phase and predict the clinical performance of amalgam restorations. this was subsequently adopted as one of the prime tests in both the American Dental Association (ADA) and the FDI World Dental Federation (FDI) specifications (16).

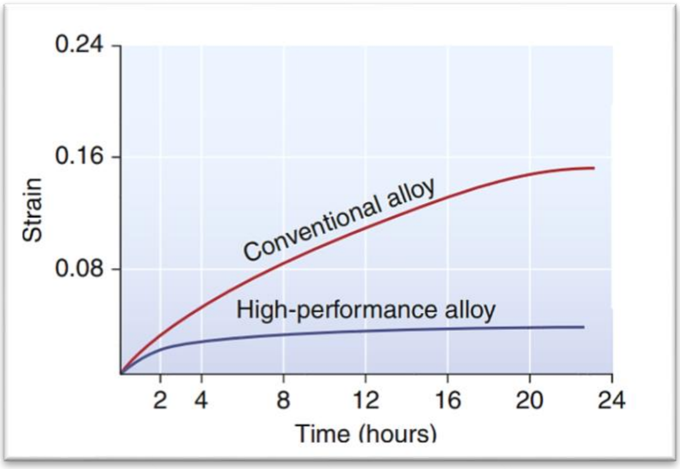


Fig.9: Creep curves for conventional (low-copper) and high-performance (high-copper) amalgams.

To test creep of amalgam, according to the ADA specification number 1 for dental amalgam published in 1976 and revised in 1979. Creep test conducted on specimens, where the axial length of each specimen shall be measured and recorded as original length. The specimens shall be stored at 37± 3oC for seven days. A stress of 36 MPa shall be applied continuously to the specimen for not less than four hours at 37±3°C. The change in length between the one-hour and four-hour readings shall be recorded and the creep shall be computed as follows: creep (%) equals length change between one and four hours divided by original length multiplied by 100. The average of the creep for the specimens shall be recorded to the nearest 0.1%. the acceptable creep value in a dental amalgam should be less than 3% (17).

Sag is the permanent deformation potential of long-span metal bridge structures at porcelain-firing temperatures under the influence of the mass of the prosthesis. Sag resistance is the ability of a dental alloy to resist deformation under its own weight during porcelain-firing and soldering. It is particularly important in long-span bridges, where due to increased weight of the prosthesis, the porcelain-firing temperatures may cause the unsupported alloy substructure to deform permanently, distortion of the framework of long span bridges during the firing process may occur, which results in an ill-fitting restoration. Therefore, the 'sag' phenomenon affects the metallic substructure and is of vital importance to the overall fit of ceramo-metal restorations (1).

Metals used in dentistry for indirect restorations for porcelain veneers have melting temperatures that are much higher than mouth temperatures, thus, they are not susceptible to creep deformation intraorally. As well, should be compatible with porcelain veneering, having their melting temperature significantly higher than the firing temperature of the porcelain. The metal framework must not melt during porcelain firing and must resist high temperature "sag" deformation (1).

Some alloys used for metal-ceramic prostheses can sage at porcelain veneering temperatures. Earlier gold alloys were used for ceramo-metal restorations, these alloys had certain disadvantages like low modulus of elasticity and poor sag resistance during the porcelain firing cycle. The highest sag rate was found with high gold alloys (gold-platinum pallidum alloys), whereas gold-palladium and palladium-silver based alloys had lower rates. Due to sagging caused by thermal creep of the alloy, distortion of the framework of long span bridges during the firing process may occur, leading to an inaccurate fit of the restoration (18).

Base metal alloys have substituted the use of gold alloys by having higher hardness and greater rigidity. This allowed the fabrication of long span with lesser thickness, enabling the coping to reach 0.1 to 0.2 mm thick. Moreover, higher melting range reduces the risk of distortion and sagging of metal substructure during porcelain firing which led to use of base metal alloys for fixed restorations, these materials are far more stable at porcelain firing temperatures than the gold-based alloys due to their superior sag resistance. Most of the non-precious alloys used are based on nickel chromium and cobalt chromium (18).

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