CHAPTER 2

PLASTICS AND THEIR BEHAVIOUR UNDER TEMPERATURE AND STRESS

2.1 TYPES OF PLASTICS

The plastics that are finding acceptance today, are basically synthetic organic materials called resins. These resins consist of two or more elements processed in a precise fashion to obtain a specific end product. Generally speaking, there are two broad classes of plastics. One is known as thermoplastics, the second as thermoset plastics. For each class, the properties, physical characteristics, and methods of fabrication used for converting the plastic into an end-product are directly dependent upon the way their chemical “building blocks” are assembled.

Thermosetting polymers differ from thermoplastics in the way they react to heat (Crawford 1998). With thermosetting polymers, the reaction is chemical and the polymers combine, in what is termed “cross-linking, to form a new structure with new properties. During molding, polymer molecules capable of further reaction are chemically cross linked into a network structure. The network structure is held together by primary bonds so that the material cannot be softened again by application of heat. If excess heat is applied thermosetting materials will degrade. Since the cross linking of the molecules is by primary chemical bonds, thermosetting materials are characteristically quite rigid and their mechanical properties are less sensitive to heat than thermoplastics. So they are not weldable.
Thermoplastic materials are characterized by the ordered assembly of a number of building blocks under the proper conditions to produce a long chain. In a thermoplastic material, the long chain-like polymer molecules are held together by relatively weak Van der Waals forces. When the polymer is subjected to heat, the intermolecular forces are weakened so that chains can move relative to each other. As the temperature is increased the polymer becomes soft and flexible and eventually, at high temperature, it is a viscous melt. When the material is allowed to cool, it solidifies. In principle, thermoplastics can be repeatedly softened by heating and hardened on cooling, and hence can be welded by the application of heat. Thermoplastics can be further divided into two types which are amorphous and semi-crystalline material (as shown in Figure 2.1(a) and 2.1b)).

Amorphous thermoplastics are generally characterized by a random molecular arrangement and broad softening temperature range that allows the material to soften gradually and flow without premature solidification. Semi-crystalline thermoplastics have a semi orderly structure resulting in sharp melting and solidification temperatures. The sharp melting point is the result of a very high energy requirement necessary to break down the semi-crystalline structure to allow for material flow. Solidification is very rapid and may occur prematurely. For these reasons special attention to joint design and energy requirements are necessary to achieve desired results. In general plastics have a higher density when they crystallize due to the closer packing of the molecules. Typical characteristics of crystalline and amorphous plastics are shown in the Table 2.1.
As the industry has grown, many standard plastic products are now readily available off the shelf. They include not only hardware such as nuts, bolts, washers, fittings, and valves, but also complete assembles, such as fan, ducts, and even laboratory equipment and accessories. The increased production and usage of plastics in many commercial products has resulted in great demand for the knowledge of fast, inexpensive assembly methods.
Table 2.1  Comparison between characteristics of semi-crystalline and amorphous thermoplastics

<table>
<thead>
<tr>
<th>Amorphous</th>
<th>Semi-Crystalline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Broad softening range-thermal agitation of the molecules breaks down the weak secondary bonds. The rate at which this occurs throughout the structure varies producing broad temperature range for softening.</td>
<td>Sharp melting point-the regular close-packed structure results in most of the secondary bonds being broken down at the same time.</td>
</tr>
<tr>
<td>Usually transparent-the loose structure transmits light so the material appears transparent.</td>
<td>Usually opaque-the difference in refractive indices between the two phases (amorphous and crystalline) causes interference so the material appears translucent or opaque.</td>
</tr>
<tr>
<td>Low shrinkage-all thermoplastics are processed in the amorphous state. On solidification, the random arrangement of molecules produce little volume change and hence low shrinkage.</td>
<td>High shrinkage-as the material solidifies from the amorphous state the polymers take up a closely packed, highly aligned structure. This produces a significant volume change manifested as high shrinkage.</td>
</tr>
<tr>
<td>Low chemical resistance-the open random structure enables chemicals to penetrate deep into the material and to destroy many of the secondary bonds.</td>
<td>High-chemical resistance-the tightly packed structure prevents chemical attack deep within the material.</td>
</tr>
<tr>
<td>Poor fatigue and wear resistance-the random structure contributes little to fatigue or wear resistance.</td>
<td>Good fatigue and wear resistance-the uniform structures are responsible for good fatigue and wear properties.</td>
</tr>
</tbody>
</table>

Examples-Acrylonitrile-Butadiene-Styrene (ABS), Polystyrene (PS), Polyvinyl Chloride (PVC), Polycarbonate (PC) | Examples-Polyethylene (PE), Polypropylene (PP), Polyamide (PA), Nylon, Polyester (PETP, PBTP). |
2.2 VISCOELASTIC BEHAVIOR OF PLASTICS

In a perfectly elastic material the stress, $\sigma$, is directly proportional to the strain, $\varepsilon$, and the relationship may be written for uniaxial stress and strain, as

$$\sigma = E \varepsilon \text{ (Hooke’s law)}$$  \hspace{1cm} (2.1)

where $E$ is referred to as the modulus of elasticity for the material.

In a perfectly viscous (Newtonian) fluid the shear stress, $\tau$, is directly proportional to the rate of strain $\gamma$, and the relationship may be written as

$$\tau = \eta \gamma \text{ (Newton’s law)}$$  \hspace{1cm} (2.2)

where $\eta$ in this case is referred to as the viscosity of the fluid.

Plastic materials exhibit mechanical properties between these two ideal cases and they are termed “viscoelastic” (Lakes 1999). In a viscoelastic material, the stress is a function of strain and time. So it may be described by an equation of the form:

$$\sigma = f (\varepsilon, t).$$  \hspace{1cm} (2.3)

This equation is not amenable for simple analysis, and often reduced to the form

$$\sigma = \varepsilon f (t).$$  \hspace{1cm} (2.4)
This equation is the basis of linear viscoelasticity and simply indicates that for a fixed value of elapsed time, the stress will be directly proportional to the strain. The most characteristic features of viscoelastic materials are that they exhibit a time dependent strain response to a constant stress (creep) and a time dependent stress response to a constant strain (relaxation). In addition when the applied stress is removed the material has the ability to recover slowly over a period of time. These effects can also be observed in metals, but only at very high temperatures. The creep and recovery of plastics can be simulated by the use of simple models.

2.2.1 Voigt Kelvin Model

The mechanical response of viscoelastic bodies such as plastics is represented by either a spring or a damper. A better model consists of a parallel combination of a spring and a damper. Such a model is called a Voigt Kelvin Model (Figure 2.2).

![Figure 2.2 The Voigt –Kelvin model](image)
It can be seen that the applied load is supported jointly by the spring and dash pot, so the total stress developed is equal to the sum of the stresses in spring element \( \sigma_1 \) and in damper \( \sigma_2 \).

\[
\sigma = \sigma_1 + \sigma_2
\]  

(2.5)

In this case the total strain \( \varepsilon \) is equal to the strain in each element,

\[
\varepsilon = \varepsilon_1 = \varepsilon_2
\]  

(2.6)

where \( \varepsilon_1 \) is the strain in spring element and \( \varepsilon_2 \) is the strain in dash pot.

From these we can get

\[
\sigma = E\varepsilon_1 + \eta\varepsilon_2
\]  

(2.7)

\[
\sigma = E\varepsilon + \eta\varepsilon
\]  

(2.8)

This is the governing equation for the Kelvin-Voigt model

2.2.2 Loss Modulus, Storage Modulus and Complex Modulus

In polymeric materials stress-strain relations are more complex than what can be explained using Hooke’s law or Newton’s law. Elastic material can store energy because stress is in phase with the strain (phase angle \( \delta = 0^\circ \)). In purely viscous response stress is out of phase with strain (\( \delta = 90^\circ \)). Viscous material can dissipate energy. In viscoelastic material the phase angle is in between 0\(^\circ\) and 90\(^\circ\) \((0^\circ < \delta < 90^\circ)\). Stress in a viscoelastic material is referred to as the complex stress*\((\sigma^*)\). The complex stress can be separated into two components
1) Elastic stress in phase with the strain
   \( \sigma' = \sigma^* \cos \delta, \) (2.9) \( \sigma' \) is the degree to which material behaves like an elastic solid.

2) Viscous stress in phase with strain rate
   \( \sigma'' = \sigma^* \sin \delta, \) (2.10) \( \sigma'' \) is the degree to which material behaves like an ideal liquid.

In the case of viscoelastic material three modules are required to define the relationship between stress and strain.

1) The Complex Modulus \((E^*)\).
   It is the measure of materials overall resistance to deformation
   \[
   E^* = \frac{\text{Stress}^*}{\text{Strain}} \tag{2.11}
   \]

2) The Elastic (storage) Modulus \((E')\).
   This modulus is the measure of elasticity of materials. It is the ability of the material to store energy.
   \[
   E' = \left[ \frac{\text{Stress}^*}{\text{Strain}} \right] \cos \delta \tag{2.12}
   \]

3) The Viscous (loss) Modulus \((E'')\).
   It is the ability of material to dissipate energy. Energy lost as heat.
   \[
   E'' = \left[ \frac{\text{Stress}^*}{\text{Strain}} \right] \sin \delta \tag{2.13}
   \]
The tangent of the phase angle is the ratio of the loss modulus to the storage modulus.

\[ \tan \delta = \frac{E''}{E'} \]  \hspace{1cm} (2.14)

“TANDELTA” (tan\(\delta\)) is a measure of the damping ability of the material-such as vibration or sound damping.

### 2.2.3 Viscoelastic Heating

A viscoelastic material which is subjected to sinusoidal strain dissipates some energy into heat through inter molecular friction. The loss modulus (\(E''\)) for a viscoelastic material is the out-of-phase modulus, and it is a measure of the energy dissipated. If the material is subjected to a sinusoidal strain, the average energy dissipated per unit time due to viscoelastic heating is given by

\[ Q = \frac{\omega \varepsilon_0^2 E''}{2} \text{ J/m}^3\text{.sec} \]  \hspace{1cm} (2.15)

where \(Q\) is the average power dissipated, \(\omega = 2\pi f\), \(f\) is the applied frequency, \(\varepsilon_0\) is the maximum strain and \(E''\) is the loss modulus.

This relationship states that power generated in the plastic increases with square of the applied ultrasonic strain amplitude \(\varepsilon_o\). By increasing the amplitude of vibration, the weld time can be effectively shortened. This demands more power from the equipment. As the frequency decreases, to obtain equivalent heating, the vibration amplitude must increase.
2.3 EFFECT OF TEMPERATURE ON BEHAVIOR OF PLASTICS

The nature of viscosity is such that temperature is of fundamental importance (Strong 1996). In plastics, the primary bonds are strong covalent bonds along the molecular chains and these are not unduly affected by extremes of temperature unless the degradation temperature is exceeded. However, the secondary forces, bonding chains together and restricting their relative movements and rotations, may be overcome by an increase in temperature. This increases the thermal motion of the molecules and results in a change in the physical properties of the plastics. One of the most important differences between plastics and many other materials is the marked temperature dependence of the physical properties of plastics, even for quite small temperature variations near room temperature. This behavior is a result of the molecular mobility of the long chain polymer molecules and is particularly evident with thermoplastics.

The relative effects of a temperature increase on different plastics depend on the structure of each material and in particular whether it is amorphous or semi-crystalline. In an amorphous plastic at low temperature, there is no molecular mobility and the plastic material is rigid and glassy. As the temperature is raised, segments of the molecules are able to move. At higher temperatures more and larger segments can move and the modulus drops. The largest change in modulus is at the glass transition temperature ($T_g$). Above $T_g$, squeeze flow and intermolecular diffusion can take place, and the material is considered to be rubbery.

A semi-crystalline plastic material’s behavior is similar to that of an amorphous plastic below $T_g$, i.e. it is rigid and glassy. Above $T_g$ the amorphous material becomes rubbery, but the semi-crystalline plastics remain
rigid. Semi-crystalline polymers require higher energy levels to soften or melt than amorphous resins because they have an orderly structure, resulting in a sharp melting temperature. Therefore, semi-crystalline plastic material requires longer heating times and higher temperatures. On further heating the melting point \((T_m)\) is reached. Above \(T_m\) the semi-crystalline plastic is a viscous melt. In general, for semi-crystalline plastics the melting temperature must be exceeded before squeeze flow and diffusion can take place.

2.4 MATERIAL WELDABILITY

Frequently the term “weldability” is used because it is extremely convenient to express the ability of a material to be welded. In a broad sense, weldability might be taken as the relative ease by which a material can be welded to produce satisfactory joints. The American welding society defines weldability as “the capacity of a material to be welded under the fabrication condition imposed, into a specific, suitably designed structure and to perform satisfactorily in the intended service”.

The ultrasonic weldability of thermoplastic material depends on many variables (Miller 1983). The most significant variable is the ability of the material to pass ultrasonic energy into the weld interface. The two important variables are storage modulus and loss modulus. The storage modulus is related to the material’s ability to store energy. The loss modulus describes the material’s ability to dissipate energy through intermolecular friction mechanisms. Other variables that affect weldability are melt temperature, density, the thermal conductivity, the specific heat and velocity of sound as well as resultant wavelength.

The two types of thermoplastics-amorphous and semi-crystalline-react differently when heated. Amorphous polymers are characterized by a
random molecular arrangement and a broad melting or softening temperature range that allows the material to soften gradually and flow without premature solidification. For amorphous polymers, squeeze flow and intermolecular diffusion can take place at temperature greater than the glass transition temperature. Ultrasonic welding of this material is very efficient, requiring low energy input for energy transmission. ABS is an example of an amorphous plastic with excellent welding characteristics, and it can be welded to itself, acrylic and ABS/Polycarbonate (Cycolony800) (Devine 2001).

Crystalline resins have a critical melting temperature. There is no softening or melting leading up to this particular temperature. Upon reaching the critical temperature, melting occurs instantaneously. Premature solidification is a problem with crystalline resins and must be considered in joint design. For semi-crystalline polymers, the melting temperature must be exceeded before squeeze flow and intermolecular diffusion can take place. Solidification is very rapid and may occur prematurely. For this reason, special attention to joint design and energy requirements is necessary to achieve the desired results.

The weldability of thermoplastics is affected by three main factors: heating method, squeeze flow, and inter-molecular diffusion. For a thermoplastic to have good weldability it must be quickly heated, flow easily (squeeze flow), and must have enough chain mobility for rapid diffusion. In ultrasonic welding, high frequency vibration is applied to parts. This results in cyclical deformation of surface asperities. Eventually, the surface asperities melt and flow and the parts are welded. The materials that are most suitable for ultrasonic welding are those with a high loss modulus. However, if the parts are long and the vibration energy is applied far from the weld area, then the material should have a high elastic modulus and a relatively low loss modulus. Otherwise, the ultrasonic energy is dissipated prior to reaching the
weld area. The ultrasonic weldability of thermoplastics depends upon their capacity for transmitting vibration and temperature of fusion. Many physical variables affect weldability. To determine weldability, testing must be done on the individual part, to select the best joint design and other weld parameters.

2.5 SUMMARY

This chapter discussed the behavior of polymers (amorphous, semi-crystalline) with changes in temperature and their relevant properties to make them weldable by the application of pressure and temperature. The detail of joining them by ultrasonic welding is discussed in the next chapter.