Definitions of simulation outputs in Moldex 3D for Shell module

The simulation outputs provided by Moldex 3D for Filling/ Packing/ Cooling and Warpage Analysis in Shell module are defined as follows.

Filling/ Packing Analysis

Melt Front Time

Melt front advancement is a position indicator as melt front boundary movement in different time duration in the filling process. With Melt Front Time, users can check the filling dynamics of the polymer with the animation function to understand how the polymer fills in the cavity. Especially, it is very important to realize whether the cavity fills completely or not.

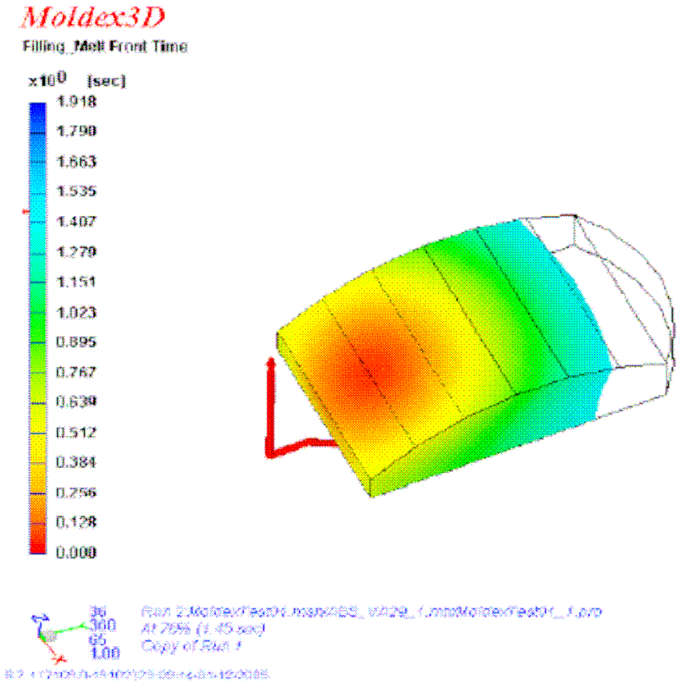

Fig 1-1. Melt Front Advancement at 75 % of Fill Time

Central Temperature

The temperature distribution of the central layer (or mold parting line) along the thickness is shown in Fig 1-2. As illustrated in the figure, the central temperature generally represents the high temperature region of the melt across the thickness direction during the filling process. During the filling process, the melt is pushed into cavity. At the same time, melt also accumulates the energy combining the shear heating with solid wall, the heat conduction through solid wall to the mold base and cooling channel, and the heat convection inside of the melt. The central temperature can be used to predict how easy the melts can be cooled down. However, if there is a large area of low central temperature distribution, it is pretty easy to be cooled and frozen, which might result in short shot.

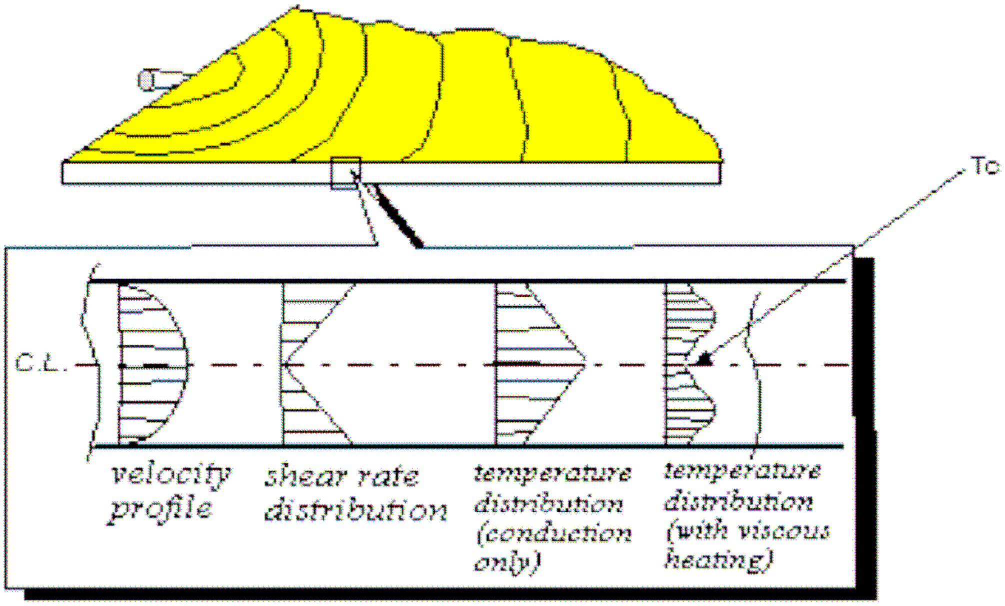

Fig 1-2 The central temperature in the melts of cavity.

Average Temperature

The distribution of average temperature across the thickness direction is shown in Fig. 1-3. The value of the average temperature is defined in equation below. Since the melt temperature varies during the filling process, Moldex3D shows the distribution only at the end of filling. As illustrated in the figure, the average temperature can be regarded as an average value of the plastic part during the filling stage along the thickness direction. They also show how thickness effects the temperature distribution. In general, average temperature distribution of polymers can be applied to evaluate the possible location of hot spot and treated as a reference to cooling pipe arrangement.

$$T_a = \frac{\int_0^b T dz}{\int_0^b dz}$$

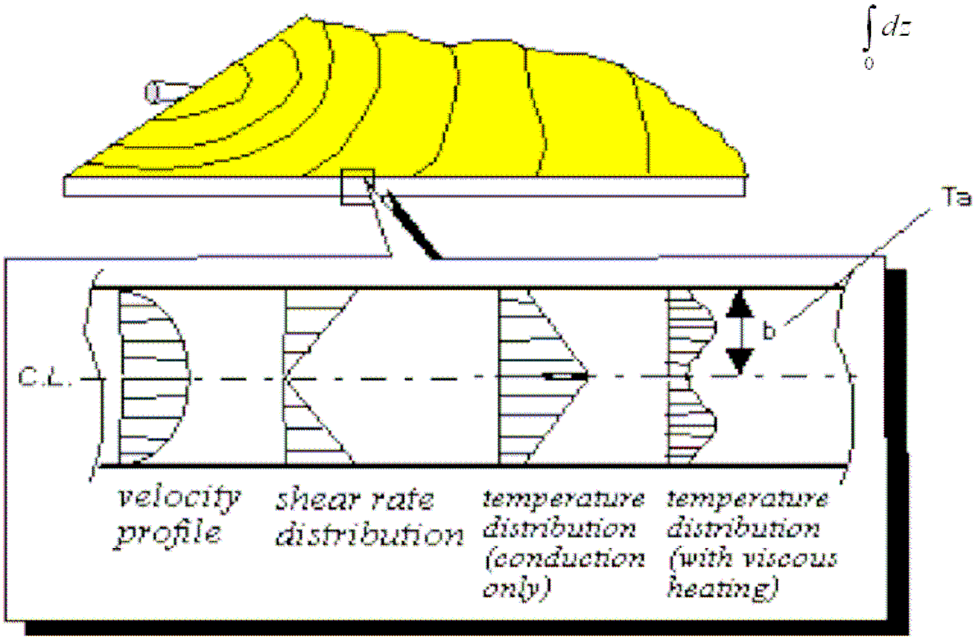

Fig 1-3 The Average temperature in the melts of cavity

Bulk Temperature

The velocity-weighted average temperature distribution is defined in equation below. Bulk temperature represents a dynamic average temperature. The key point as described in the equation is to apparently demonstrate how heat convection affects the melt temperature and the temperature distribution of hesitation area and viscous heating area. Normally, bulk temperature distribution can reflect the ‘trends’ or ‘paths’ of filling flow during the filling process.

$$T_a = \frac{\int_0^b Tu\,dz}{\int_0^b u\,dz}$$

Pressure

Pressure is defined as normal force per unit area. The feature of the pressure distribution is an indicator to examine the pressure drop during filling stage from the runner to the gate, and to the mold cavity. Based on the pressure drop and distribution, users can revise the part and mold design. In addition, the multiple gates system in one cavity or the multiple cavities system, the pressure distribution is a good indicator to inspect the flow balance.

Volumetric shrinkage

Volumetric shrinkage shows the variation percentage of part volume due to the PVT characteristics of polymer. In general, positive value represents volume shrinkage while negative value represents volume expansion. Normally, under the same packing temperature and pressure conditions, the specific volume for crystalline polymers has a higher value than non-crystalline polymers in high temperature areas. The condition in low temperature areas is completely different. Crystalline polymer has a lower value of specific volume than non-crystalline polymers. Variation of specific volume is more significant for crystalline polymers than for non-crystalline polymers. Polymer has a higher specific volume when packing pressure is decreasing. Packing pressure and temperature are the most important variables in controlling the specific volume and density of plastic parts.

The shrinkage of plastic parts is determined by their packing conditions. Since the mold temperature is lower during packing stage and the molten polymer is constantly being cooled. The density and viscosity of polymer keep going up which makes molten polymer from the gate difficult to replenish the volumetric change. Therefore, the energy required to compensate plastic shrinkage is decided by packing pressure and its transmission time span inside the cavity. Shrinkage depends on packing pressure and packing time.

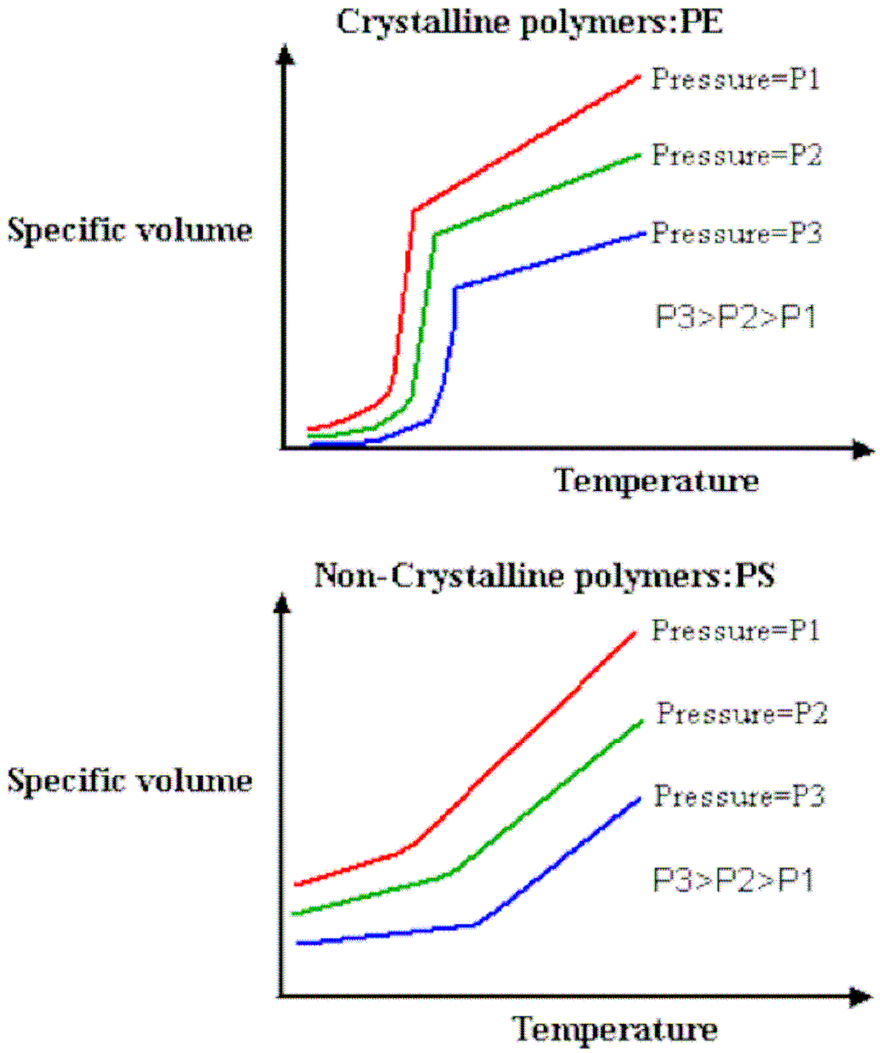

Fig 1-4 The PVT features of crystalline and non-crystalline polymeric materials

Shear Stress

During the filling process, the viscous behavior of polymeric fluids will generate the shear stress. In general, the distribution can be used to predict the quality of product if it is not balanced. It will further result in warpage deformation of the finished products. In addition, when the shear stress is very high, it could force the molecular chains of polymers to be highly stretched or oriented, even broken. The recoil of highly stretched molecular chains has been proven to be the main issue in warpage.

Specifically, shear stress is defined as elemental-area-weighted average of wall shear stress of surrounding elements shown below.

$$ShearStress = \frac{\sum A_i \tau_{w,i}}{\sum A_i}$$

where $\tau_{w,i}$ is the wall shear stress of the *I th* element; *A i* is the elemental area of the *ith* element.

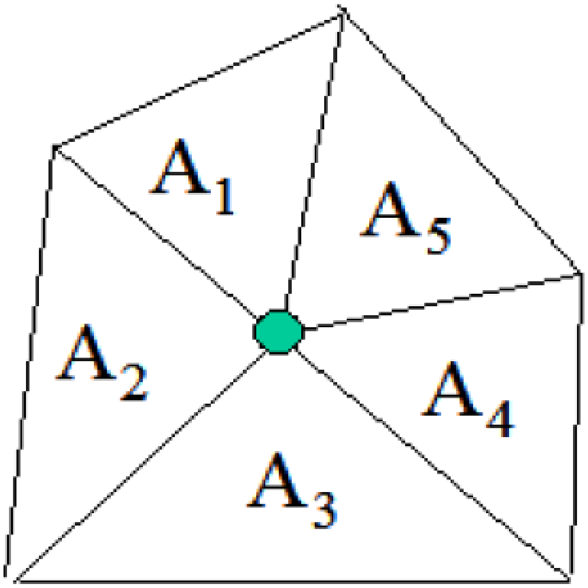

Fig 1-5 Elemental-area-weighted average of wall shear stress of surrounding elements

Shear Rate

Shear rate is the rate of shear deformation of the material during the polymer processing. A higher shear rate of polymer is equivalent to a higher rate of deformation, i.e. the molecular chains were drastically deformed. Therefore, shear rate distribution is related to the variation of velocity gradient and molecular orientation.

Specifically, shear rate is defined as elemental-area-weighted average of maximum gapwise shear rate of surrounding elements shown in equation below.

$$ShearRate = \frac{\sum A_i \dot{\gamma}_{\max,i}}{\sum A_i}$$

where $\dot{\gamma}_{\max,i}$ is the maximum shear rate in the gapwise direction of the *ith* element; A_i is the elemental area of the *ith* element.

Normally, high shear rate occurs at gates and thin cavities. If the shear rate is too high, (for example, > 10,000 1/sec), it could deform the molecular chains even to break and then weaken the strength of product.

Density

It shows the density distribution of the polymer at the end of fill condition. In general, frozen region will show a greater value of density and molten region will have a lower density value. Non-uniformity in density is a source of part warpage.

Melt front temperature

Melt front temperature is the temperature value of the plastic melt as it reaches the given point. This value indicates how heat is conveyed and dissipated during the molding phases.

Frozen Layer Ratio

It shows the percentage of frozen layer to part thickness. This value will approach 100% as time proceeds when the part is frozen completely.

Temperature Rise (Viscous Heating)

It shows the difference between average temperature of plastic melt at end of filling and the melt entrance temperature. Melt temperature is risen due to viscous heating (frictional heating).

Velocity Vector

It shows velocity of the plastic melt at the end of filling.

Cooling Analysis

Avg. Part Temperature

This is the thickness-average temperature T_{avg} distribution of part at the End of Cooling (EOC).

$$T_{avg} = \frac{\int T(x)dx}{H}$$

Avg. Part Temperature (Front)

This is the cycle-averaged temperature of the front face of the part at EOC. The front face of the part is defined as the surface forward to you in the screen. Usually it shows the cavity-side surface temperature.

Avg. Part Temperature (Back)

This is the cycle-averaged temperature of the back face of the part at EOC. The back face of the part is defined as the surface opposite to you in the screen. Usually it shows the core-side surface temperature.

Avg. Mold Temp. Difference

This value means the cycle-averaged temperature difference between the top and bottom mold halves. This value should be as small as possible to obtain quality molded part. Greater mold temperature indicates unbalanced mold cooling across the part thickness and is a primary resource of part warpage (due to thermal bending), For precision molding the mold temperature difference should be controlled under 5 °C.

Center Temperature

It shows the temperature of the middle layer in the thickness direction of the part at the end of cooling (EOC).

Max. Temperature

It shows the maximum temperature in the thickness direction of the part at the end of cooling (EOC).

EOC Part Temperature (Front)
This is the temperature of the front face of the part at the end of cooling (EOC).

EOC Part Temperature (Back)
This is the temperature of the back face of the part at the end of cooling (EOC).

EOC Mold Temperature (Front)
This is the temperature of the front face of the mold that is contacted with part at the end of cooling (EOC).
EOC Mold Temperature (Back)
This is the temperature of the back face of the mold that is contacted with part at the end of cooling (EOC).

Avg. Heat Flux (Front)
This is the heat transfer rate in normal direction of the part element per unit area of the front face. Heat flux between the surface and cooling channel displayed in the screen during cooling phase. This value means the cycle-averaged heat dissipation rate per unit area (flux) of part-mold interface that can be seem by the observer on computer. A higher heat flux value indicates the better cooling efficiency.

Avg. Heat Flux (Back)
This is the heat transfer rate in normal direction of the part element per unit area of the back face. Heat flux between the surface opposite to you and cooling channel displayed in the screen during cooling phase. This value means the cycle-averaged heat-dissipation rate per unit area (flux) of part-mold interface that is opposite (hidden) to the front face. A higher heat flux value indicates the better cooling efficiency.

Heat Load (Front)
This is the heat load of the front face of the part. Head load is the quantity of heat released from the plastic part per cycle time.

Heat Load (Back)
This is the heat load of the back face of the part. Head load is the quantity of heat released from the plastic part per cycle time.

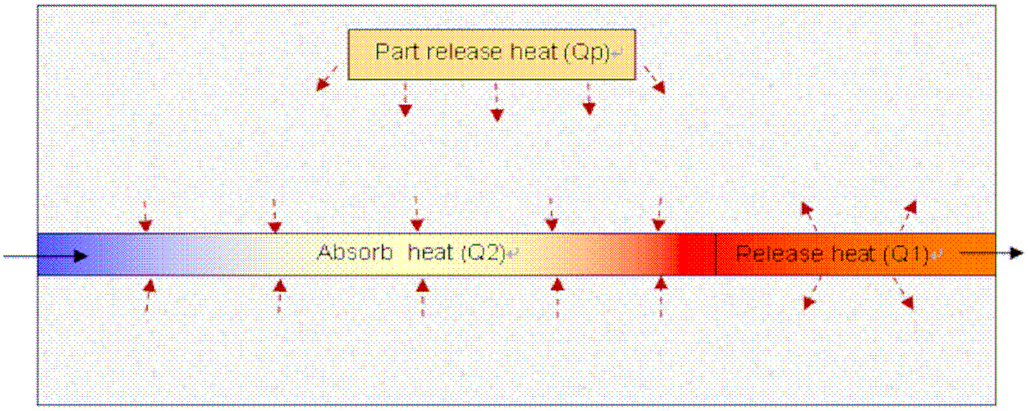

Fig 1-6 Cooling channel cooling efficiency

Heating Efficiency

This is the heating efficiency of the cooling channel. If Q1 is the total released heat through one cooling channel surface and Qp is the released heat of the part during molding cycle, the heating efficiency of the cooling channel is defined as Q1/Qp*100%. This data shows the percentage of total heat released by the heating channels as shown in Fig. 1-6.

Cooling Efficiency

This is the cooling efficiency of the cooling channel. If Q2 is the total absorbed heat through one cooling channel surface and Qp is the absorbed heat of the part during molding cycle, the cooling efficiency of the cooling channel is defined as Q2/Qp*100%. This data shows the percentage of total heat withdrawn by the cooling channels as shown in Fig. 1-6.

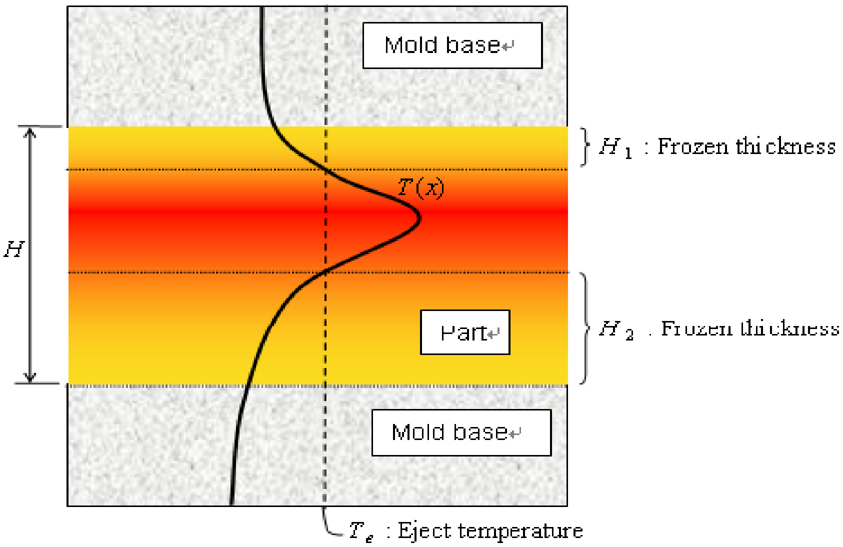

Fig 1-7 Frozen layer is defined that part temperature lower than eject temperature

Frozen Layer (Front)

This is the thickness of frozen layer (defined as the layer that has a temperature value lower than the ejection tempertature) of the front face at the end of cooling (EOC) as shown in Fig. 1-7.

Frozen Layer (Back)

This is the thickness of frozen layer (defined as the layer that has a temperature value lower than the ejection tempertature) of the back face at the end of cooling (EOC) as shown in Fig. 1-7.

Frozen Layer Difference

This is the thickness difference of top and bottom frozen layers at the end of cooling (EOC). This difference will be zero for uniform cooling as shown in Fig. 1-7.

Frozen Layer Ratio

This is the thickness ratio of top and bottom frozen layers at the end of cooling (EOC). This value will approach 100% as time proceeds as shown in Fig. 1-7.

Cooling Channel Flow Rate

This is the volume flow rate of cooling channel.

$Q = AV$

where A is the channel cross-section area, V is the flow velocity.

Cooling Channel Reynolds Number

Reynolds number is a dimensionless number, which is defined as below:

$$\mathrm{Re} = \frac{\rho V D}{\mu}$$

where • is the density; V is the flow velocity; D is the channel diameter; • is the dynamic viscosity.

Flow type	Reynolds number
Laminar flow	2300<Re
Transition flow	2300<Re<10000
Turbulent flow	Re>10000

Because the turbulent flow has better cooling efficiency than laminar flow, most popular process settings are set as the turbulent flow.

Cooling Channel Pressure

This is the pressure difference of cooling channel from the outlet to inlet,

$$P = \frac{F}{A}$$

where F is the force; A is the area.

Warpage Analysis

Displacement

Displacement refers to the deformation of part caused by process-induced shrinkage and distortion. It is the difference between the dimensions of cavity and molded part. For the displacement in the x direction, it represents the displacement of parts along the x direction. Positive value denotes the quantity of distortion along the positive (+) x direction, while negative value is along the negative (-) x direction, which is as shown in Fig.1-8.

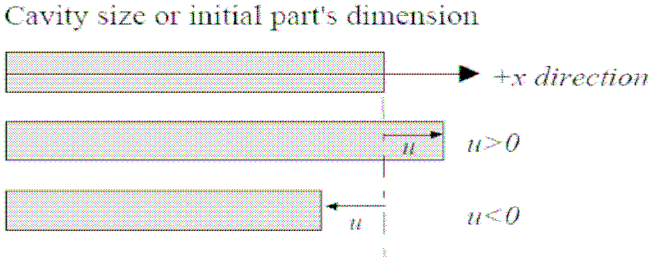

Fig 1-8 Definition for the Displacement

Displacement in y axis and displacement in z axis have the same definition as displacement in x direction. Besides, the linear shrinkage in one direction can be defined as the maximum displacement divided by the part’s dimension in this direction; that is:

Moldex3D provides several results to help users understand the causes of warpage, such as total displacement, thermal displacement and fiber orientation effect displacement.

$$\text{Max. Displacement in x direction} \approx u_{max} - u_{min}$$

$$\text{Linear shrinkage in x direction} \approx \frac{u_{max} - u_{min}}{L_x} \times 100\%$$

(X, Y, Z) Total Displacement

These displacements indicate total displacement occurring from the end of filling till the part cools down to the room temperature. It includes all factors affecting the behavior of warpage.

(X, Y, Z) Thermal Displacement

These displacements indicate the displacement that occurs from the ejection to the time the part has cooled to room temperature. Only the variation of temperature is considered.

(X, Y, Z) In-mold Constraint Effect Displacement

These displacements mean the displacement that occurs from the end of filling to the time the part is ejected. Here the mold constraint is considered.

(X, Y, Z) Fiber Orientation Effect Displacement

The fiber orientation effect deformation is defined as the difference between the following two deformations: (1) Final deformation due to all factors. (2) Deformation due to the random orientation of fiber. It presents the anisotropic effect of fiber orientation.

(X, Y, Z) Random Fiber Orientation Effect Displacement

These displacements indicate displacement that occurs from the end of filling to the time the melt has cooled to room temperature due to the fiber orientation effect.

Flatness

Flatness is the distance from selected node to reference plane. In Moldex3D, the reference plane can be defined by three ways: (1) Defined by one element; (2) Defined by three nodes; (3) Defined by plane equation.

Anisotropic Properties

The polymer without fillers mixed is assumed as isotropic material. It has isotropic material properties. On the other hand, the polymer with fillers mixed is assumed as anisotropic material. The fiber-filled polymer is one of anisotropic materials. Its anisotropic properties are depended on fiber orientation patterns. Furthermore, the anisotropic properties are obtained by integrating fiber orientation patterns and composite theory.

Moldex3D/Solid-Warp provides the distribution of stiffness modulus to help user understand the anisotropic characteristic of the part.

- The major modulus means the maximum stiffness modulus.
- The mean modulus means the mean stiffness modulus.
- The minor modulus means the minimum stiffness modulus.
- The x-axis modulus means the stiffness modulus along x-axis direction.
- The y-axis modulus means the stiffness modulus along y-axis direction.
- The z-axis modulus means the stiffness modulus along z-axis direction.

Gas Assisted Injection molding

Although the gas assisted injection molding applies the gas to enhance the injection molding process, the injection process is still similar as conventional injection molding. Therefore, many simulation outputs are similar as Shell-Flow/Pack/Cool/Warp. Here we only describe the special items.

Gas Front Time

It shows the gas front advancement. Basically, it is similar with that of melts.

Skin Ratio

Skin ratio is the fraction of the plastic material at the node at EOF/EOP in a gas-assisted injection molding process.

Skin Ratio = (the thickness of plastics after core-out by gas phase)/(the total thickness). Hence, if Skin Ratio equals to 1, it standards a full-plastic material node; if the value is smaller than 1, it‘s indicated part of the material has been core-out by gas phase.