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KEP

Residual Stress in Plastics Parts

R&D Center

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1. Scope

Injection molding is a widely used method to fulfill mass production requirements ranging from commodities to high value products such as accurate parts, automotive parts, magnet optical storage mediums, etc., using high molecular resins like plastics and rubber. Deformation due to issues such as residual stress and bending and shrinkage in the injection molding process can dramatically impact product quality, so to address this, proper understanding and effort are necessary.

Residual stress for plastics is caused by heat and flow. A given part's internal residual stress distribution is reported to form tensile stress at the center point of thickness and compressive stress on the surface.

Residual stress originates in the residual deformation, occurring during solidification even without external force; it can also occur while completely solidified.

In particular, under long term usage or while exposed to higher temperatures, residual stress in the injection part can be a factor of deformation based on the plastic's viscoelasticity characteristics and this deformation can reduce dimensional stability and, in severe cases, can cause cracks, destroying injection parts.

Thus, residual stress in the injection molding process is a very important factor. As such, it is necessary to set up optimized injection conditions to minimize this, and for this, reliable measurement of internal residual stress in the part can be properly attained.

The reasons for residual deformation are generally observed as detailed below:
(1) Deformation due to flow speed of resin in the cavity or uneven flowing speed
(2) Deformation due to indentation pressure
(3) Heat deformation due to huge temperature gap between cavity and core
(4) Deformation due to uneven cooling speed caused by shape or irregular thickness
(5) Mechanical deformation due to ejector pin or ejection problems

Residual deformation consists of intramolecular and intermolecular deformation. In normal temperatures, stress occurs on the intramolecular level, the intermolecular level, however, is metastable and the molecule chain is frozen so it cannot be the cause. However, stress can also occur when the material thaws or soaks in chemicals. Residual deformation can occur in both crystalline and amorphous resins.

2. Reasons for residual stress and methods of reduction

Residual stress in plastics injection parts is widely divided into micro and macro stress based on the reason of occurrence. Micro stress occurs when a polymer's molecular orientation is not released but instead frozen during the filling and packing process in the cavity. Macro stress, however, occurs because of internal pressure during cooling in the mold or shrinkage caused by uneven cooling speeds, insert (or outsert)'s thermal expansion, or also external pressure (deformation due to interference during ejection).

Generally, parts injected at high mold temperatures have relatively lower residual stress but done at low mold temperatures experience relatively higher residual stress which must be

reduced. Annealing is a general method to reduce residual stress. Annealing temperature has to be higher than each plastic's glass transition temperature in theory, that stress relaxation might be rapidly achieved. However, this temperature level can also cause bending and warpage, so annealing has to be done quickly within the maximum limit of dimensional change caused by stress relaxation. A given part's annealing temperature has to be adjusted based on the usage temperature and it can be assumed to progress under adequate circumstances recommended by each resin.

3. Measuring methods for residual stress

The initial measurement method for residual stress was mainly used to identify the reason for metal structure's strengh decline, particularly for strength measurement at the welding point. If residual stress exsists in plastic as well, it can cause structural weakness, so the importance of measurement continues to play a role. Measurement methods were once destructive, but preference is growing for nondestructive methods.

3.1. Measurement of residual stress - Nondestructive methods

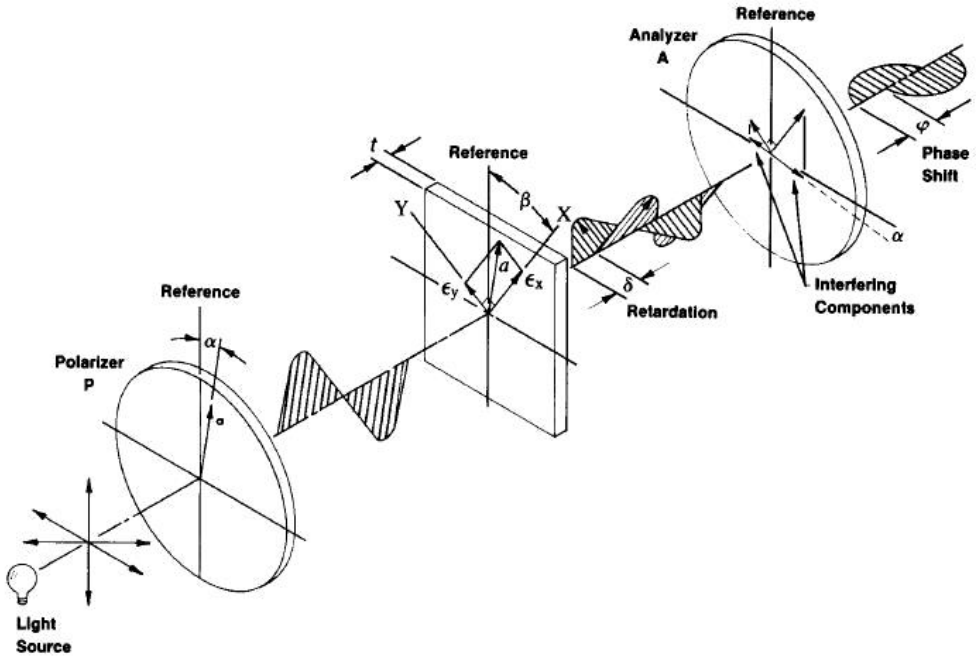
Nondestructive measurements of residual stress are summarized below:

Method	Features	Disadvantage
Curvature measurement	Measurement with Stoney Formula for a thin film substrate's entire level of bending deformation generated from interface constraint	Evaluates only the average stress of a thin film's surface due to forming only a single curvature among a long range (Impossible to evaluate uneven stress)
X-ray diffraction method	Evaluation of residual deformation from diffraction peak's width and transition rate at point of occurrence generated from the change of lattice constant caused by axial stress (residual stress)	Requires the information of modulus of elasticity, Poisson's ratio, non-stress status, surface interval distance (Measurement result is influenced by fine structure factors such as orientation)
Neutron diffraction method	Complement of X-ray diffraction method's issues	Less scattering strength, difficult to find neutron source
Magnetism Barkhausen Noise	Measurement of the differentiate level of a material's magnetization behavior due to an external magnetic field according to axial stress (residual stress)	Applies to only ferromagnetic material. Heavily influenced by fine structure
Ultrasonic wave speed	Using initial speed of ultrasonic wave speed under standard non-stress status and acoustoelastic constant	Impossible to check the axial stress(residual stress) distribution in local areas, ultrasonic wave speed experiences sensitive shifts due to fine structure/measuring temperature
Raman spectroscopy	Measurement of the property related to atomic bonding, using frequency variation of short wavelength razor reflective wave which causes a resin's own phonon vibration and scattering	Only few materials have a fixed stress shift factor. (Diamond, Silicone, etc.)
Brittle coating method	Derived from generating cracks formed by artificial stress after thin film coating treatment on a sample's surface	Sensitive to stress. Impossible to digitize. Purpose for crystallization on the strain-gauge's measuring equipment.

(1) Polarized light method

The polarized light method is a typical nondestructive measurement method to be used for plastic analysis. One disadvantage is that it is only possible to analyze parts with a translucent or transparent color; material must also exhibit even thickness.

The relevant standard is ASTM D4093, Standard Test Method for Photo-elastic Measurements of Birefringence and Residual Strains in Transparent or Translucent Plastics Materials



[Polarizer & Analyzer is set up ± 45℃ direction from reference]

Retardation (δ_{nm}) due to a light source can be calculated by the compensator value and correction constant inserted into the below formula:

$$\delta_{nm} = R * b_{nm/division}$$

Residual stress(σ) can be calcualted by the retardation value (δ_{nm}) which is accounted for in the above formula and material and thickness(t)'s stress constant ($C_{Brewster}$) according to each temperature.

$$\sigma = \delta_{nm} / (t \times C_{Brewster})$$

3.2. Measurement of residual stress – Destructive method

Destructive measurement methods for residual stress are divided into the table below. Among these, the Hole-Drilling and Cut-method are called also strain gauge methods due to usage of the strain gauge.

Method	Features	Disadvantages
Hole-Drilling	Calculates the initial existing stress by eliminating the residual stress by boring a hole at the measuring point	Impossible to measure the residual stress for curved surfaces
Cut method	Analyzes residual stress by cutting the measuring point	Possible to change the residual stress by generating heat during cutting. Differentiated stress based on cutting point
Tg fever peak	The bigger the Tg's fever peak is, the higher the residual stress	Difficult to find exact measuring point
Solution soaking method	Checks the residual stress by generating cracks at a concentrated point of stress determined according to the solution concentration and soaking time	Influenced by solution concentration, soaking time. Difficult to digitize

(1) Hydrochloric acid soaking method (POM)

In the case of POM, hydrochloric acid is used to measure residual stress. Test methods are as below:

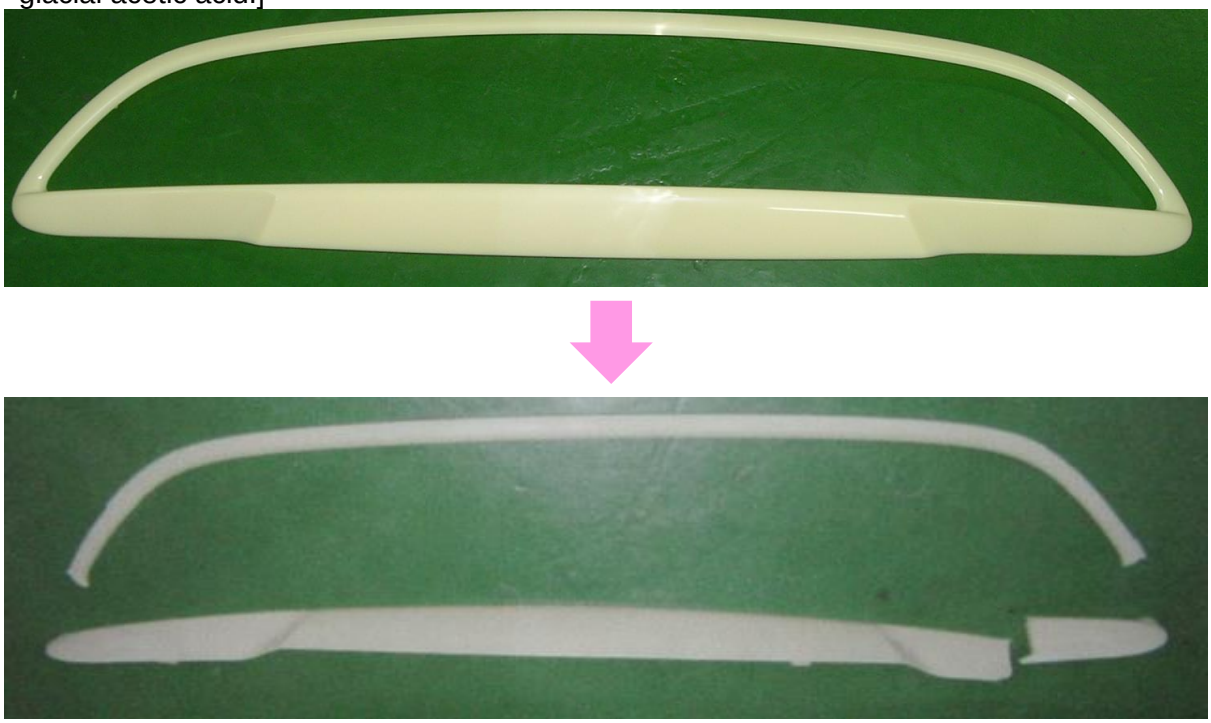
1) Define the concentration of Hydrochloric acid aqueous solution according to the detected stress.
2) From the aqueous solution with a defined concentration by dilution of hydrochloric acid maintain the temperature of the aqueous solution at 20℃.
3) If an injection part is contaminated by foreign materials like oil, it must be cleaned by methanol in the first step, and then rinsed with water in the second.
4) Soak the part slowly in the hydrochloric acid aqueous solution.
5) Leave it for 60 minutes (Cracks generally occur within 50 minutes).
6) Remove the part, rinsing with water.
7) Check the cracks.

(2) Solution soaking method

The solution soaking method is a typical destructive method used for plastics. The method is to accelerate the destruction at a concentrated point of stress by using a proper solvent for each material with an ideal concentration. It must be cautiously applied with an acid solvent and will inevitably require trial and error to identify a proper concentration and soaking time when visualizing the destruction.

The relevant standard is ASTM D1939, Practice for Determining Residual Stresses in Extruded or Molded Acrylonitrile-Butadiene-Styrene (ABS) Parts by Immersion in Glacial Acetic Acid, currently withdrawn.

[Observing cracks at the point of residual stress in ABS resin after soaking 1 minute in glacial acetic acid.]



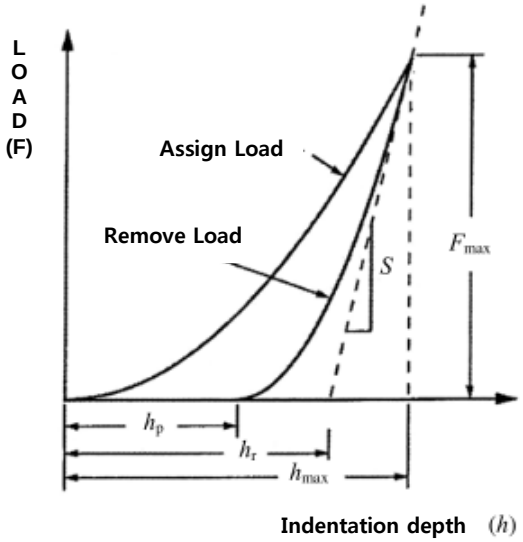
3.3. Other methods to measure residual stress

(1) Instrumented indentation test

Recently, the instrumented indentation test is used as a non-destructive technique. Originally introduced to measure metal hardness, it has been expanded to plastics materials. For testing, the measuring instrument has to be fixed, so pretreatment is absolutely necessary.

The relative standard is ISO 14577, metallic materials - Instrumented indentation test for hardness and materials parameters, KS B0951, instrumented indentation test of steel welding point. – Measurement of residual stress, total 2 cases.

Method	Features	Disadvantages
Instrumented indentation test	Calculates residual stress by measuring indentation depth variation by each indentation load (Indentation depth : < 200 um)	Needs to be a fixed vertical direction between specimen and indented impregnation

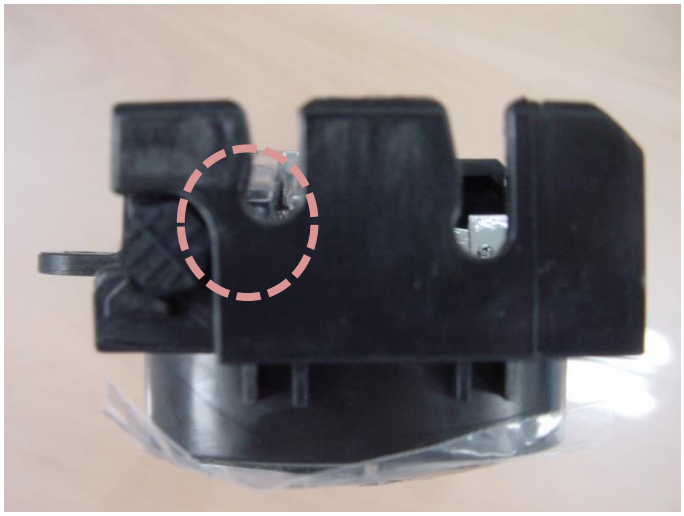


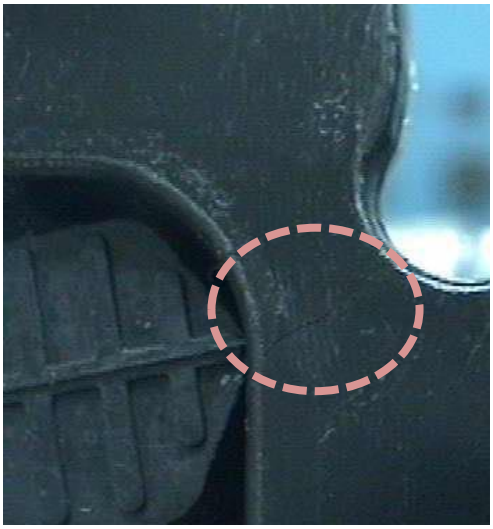
Calculates the material's hardness (H) by the depth variation (h) during indentation by changing the load(F). Residual stress (σ) is calculated for each material's contact pressure/stress ratio constant and the contact area depends on the relation between figured hardness and load.

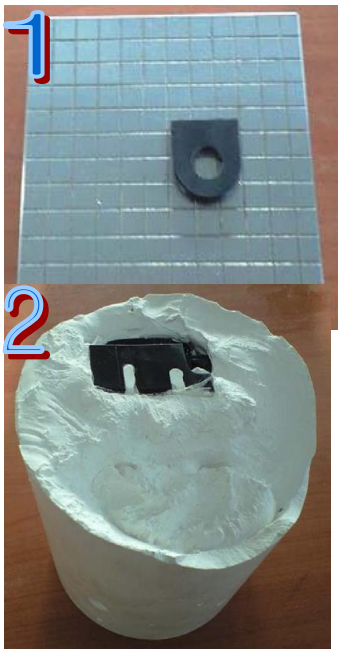
$$hc = 1.04 (hmax + \triangle ha)$$
$$H = F / (24.5h^2c)$$
$$A=F/H$$
$$\sigma = C \times (\triangle F / A)$$

(2) Instrumented indentation test case (POM)

Breakage occurred at the automotive inside door handle base part. Cracks were observed at the insert spot of the rubber part, and it is suspected to have incurred a great deal of residual stress as injection was performed with one of two cavities blocked; flow marks were also observed on the surface. As such, residual stress in this part was contrasted with a part injected and formed using two cavities in another molder.

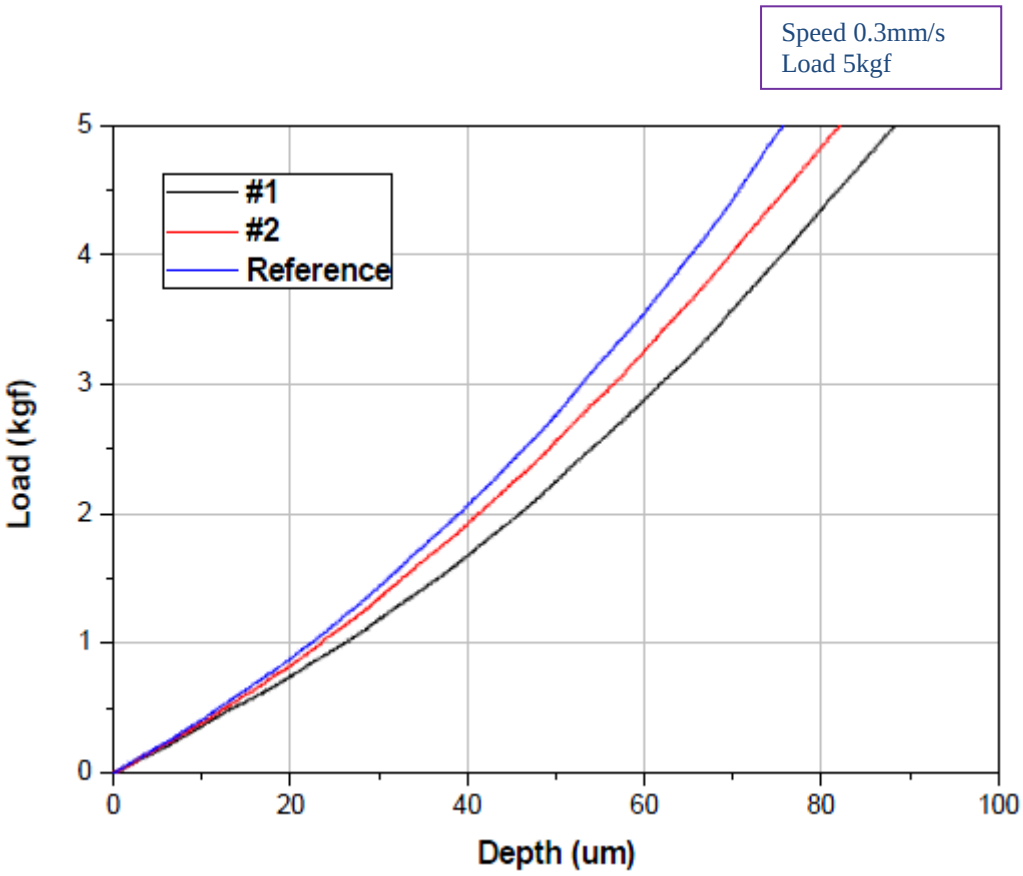






[Measuring Procedure]
(1) Sample the reference. Eliminate the stress by cutting and polishing the point furthest from the measurement point.
(2) Fix the measuring instrument. Here, it was fixed with plaster.
(3) Measure 15 times indentation/backward of under 200um depth per measuring point.

Measurement results are shown below:



Classification		Residual Stress(MPa)	Standard Deviation
Cavity #1	1	33.20	10.88
	2	24.67	7.39
Cavity #2	1	13.91	2.52
	2	13.34	2.60

The part injected by blocking one cavity (#1) has 2~3 times higher residual stress and much greater deflection than using both cavities (#2).

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