



# 자동차 경량화(Automotive lightweight) 최적화 솔루션 Autodesk® Moldflow & Helius Composite & PFA(AME)

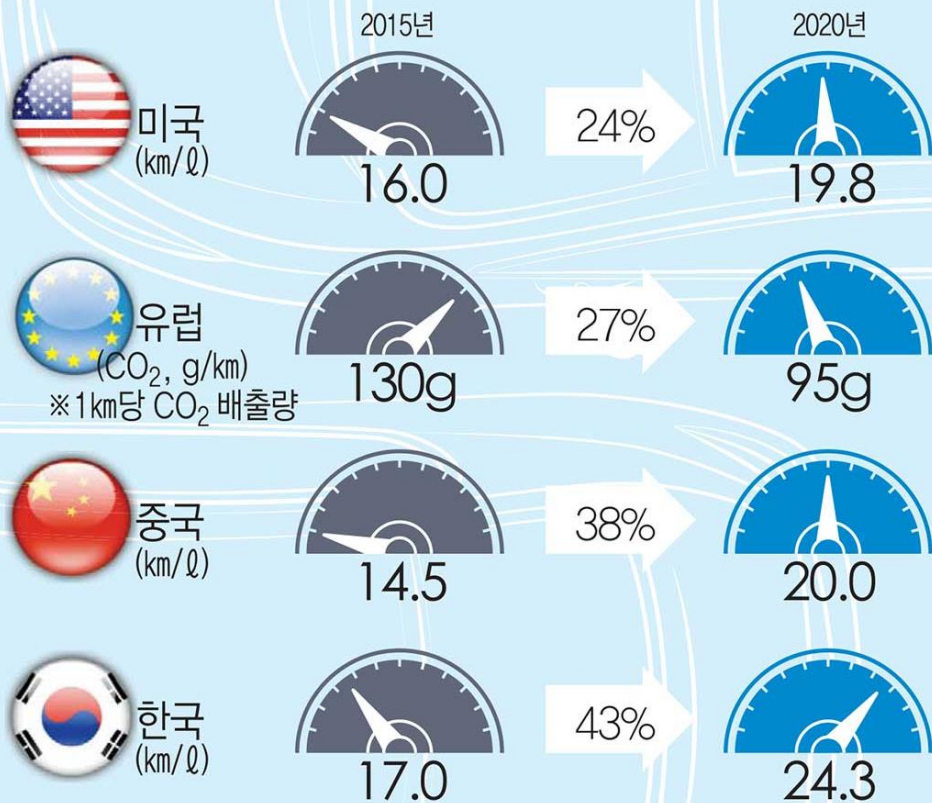
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ED&C Autodesk Moldflow Engineer

JK ED&C  
www.ednc.com

AUTODESK



# Why automotive lightweight?



## 주요국 연비 규제 강화 계획



고장력  
철강재  
신공법

- 60K 이상 초고장력 강판
- 100K 이상 비조질강
- 차체부품 핫스탬핑 공법
- 초미세립화 열처리



알루미늄화  
마그네슘화  
플라스틱화

- 저가격 성형기술 및 소재개발
- 고내열 합금 및 주조기술 개발
- 장섬유/탄소섬유 강화 소재 개발

### 경량금속과 탄소섬유 복합소재 특성

구분	알루미늄	마그네슘	복합소재
비중	2.7	1.8	1.5
강성	~70GPa	~45GPa	60~140GPa
강도	245~500MPa	250~290MPa	700~1500MPa

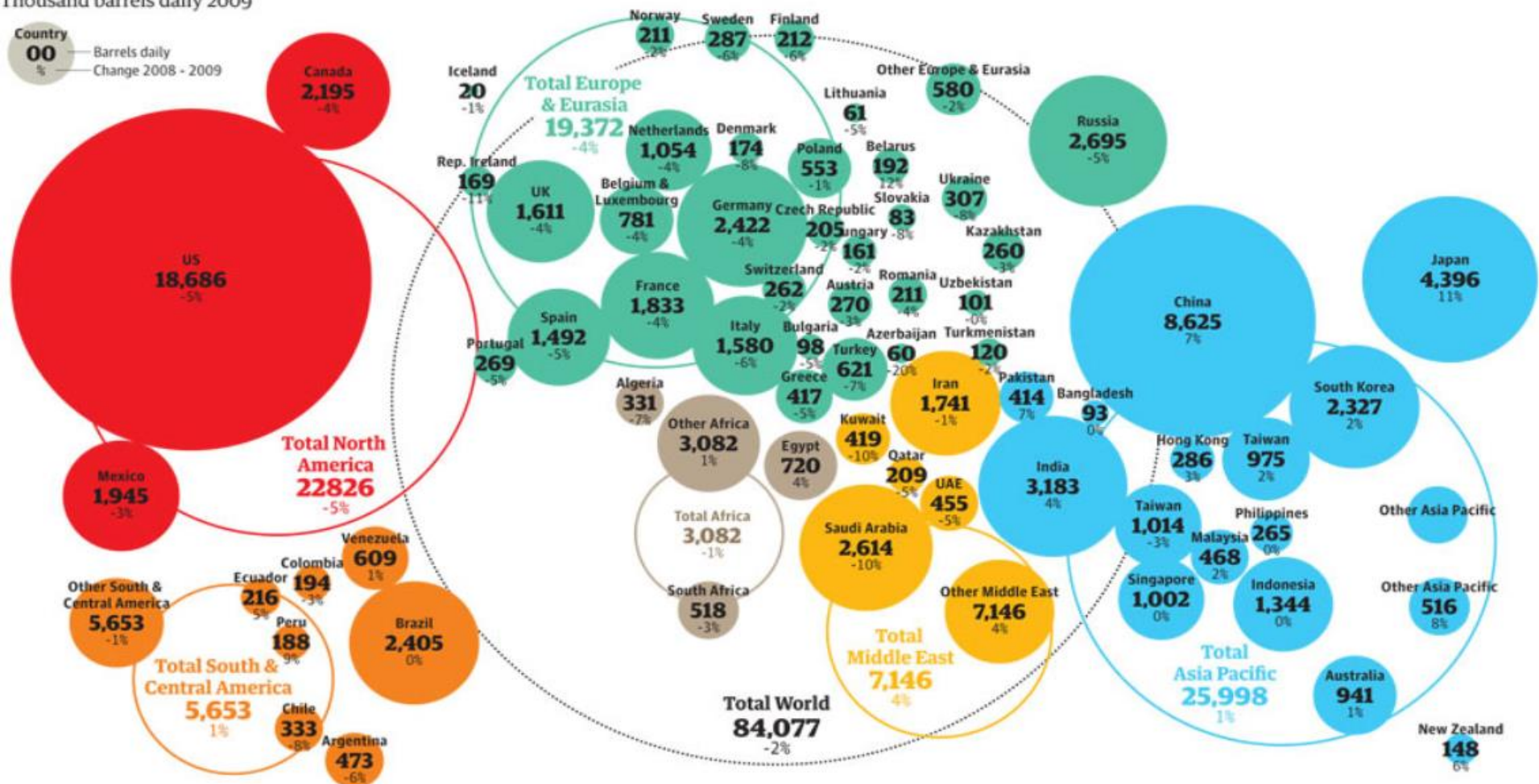
자료: 업계 취합  
© 전자신문 인포그래픽: 권태형기자



# Oil consumption around the world

Thousand barrels daily 2009

Country  
 00 — Barrels daily  
 % — Change 2008 - 2009



# Why automotive lightweight?

## 엔진/구동 효율성 향상

- Hybrid engine system
- Electrical vehicle
- High performance Powertrain/Transmission



## 주행 저항 감소

- Active flow control
- Shape optimization
- Silica rubber compound
- Tire mass reduction
- Tread pattern optimization



## 소재 경량화

- HSS/AHSS
- Magnesium/Aluminum
- Strength Optimization : M.M.M.
- Plastics/Composite
- Thin wall molding



## 소재/부품 고급화 : 고기능화

- Safety design
- Multi-functional material
- Emotional material
- Human interface system



# Why automotive lightweight?

엔진/구동계 효율향상

# Why automotive lightweight?

## 글로벌 OEM사들의 경량화 플랜

회사	Quote, Statement, or Commitment
Ford	<ul style="list-style-type: none"> <li>• From 2011 to 2020 : "Full implementation of known technology... <b>weight reduction of 250~750 lbs</b>"</li> <li>• "The use of advanced materials... offers automakers structural strength at a <b>reduced weight</b> to help improve fuel economy and meet safety and durability requirements</li> <li>• "Reducing weight will <b>benefit the efficiency of every Ford vehicle</b>. However, it's particularly critical to improving the range of PHEV and EV</li> </ul>
Toyota	<ul style="list-style-type: none"> <li>• 10~30% weight reduction for small to mid-size vehicles</li> </ul>
VW	<ul style="list-style-type: none"> <li>• "Automotive <b>light weight solutions are necessary</b>~~~"</li> <li>• "Multi-Material Concepts promise <b>cost effective light weight solutions</b>"</li> </ul>
GM	<ul style="list-style-type: none"> <li>• "One trend is clear – vehicles will consist of a more balanced use of many materials in the future, incorporating <b>more lightweight materials</b> such as nano-composites and Al and Mg."</li> <li>• Aims to shed <b>500 lb</b> from trucks by 2016, as much as 1000 lbs in early 2020s</li> </ul>
Mazda	<ul style="list-style-type: none"> <li>• Reduce each model by <b>220 lb by 2015</b>; another 220 lb by 2020</li> </ul>
Nissan	<ul style="list-style-type: none"> <li>• Average <b>15% weight reduction</b> by 2015</li> <li>• expanding the use of <b>Al and other lightweight materials</b>, and reducing vehicle weight by <b>rationalizing vehicle body structure</b></li> </ul>
Renault, Peugeot	<ul style="list-style-type: none"> <li>• Target of <b>440 lb reduction (approx. 15%)</b> by 2018</li> </ul>

113.4kg~340.2kg

226.8kg~453.6kg

99.8kg

# 경량화 효과



신규 8백만대 규모 적용  
 하루 평균 50km 주행  
 평균 연비 12km/L 기준



# 자동차 중량 구성

Approximate Vehicle mass breakdown	System	Major components in system
<p>Closures, Fenders : 8%</p> <p>Misc. : 7-8%</p> <p>Body : 23-28%</p> <p>Powertrain: 24-28%</p> <p>Suspension/ chassis : 22-27%</p> <p>Interior : 10-15%</p>	Body-in-White	Passenger compartment frame, cross and side beams, roof structure, front-end structure, underbody floor structure, panels
	Powertrain	Engine, transmission, exhaust system, fuel tank
	Chassis	chassis, suspension, tires, wheels, steering, brakes
	Interior	Seats, IP, insulation, trim, airbags
	Closures	Front and rear doors, hood, lift gate
	Miscellaneous	Electrical, lighting, windows, glazing

출처. 'Review of technical literature and trends related to automobile mass-reduction technology:

Institute of Transportation Studies, University of California, 2010)

# 경량화 소재

소재		2000년	2005년	2010년	CAGR
금속	철강	1,172(65.9)	1,161(63.3)	1,109(60.5)	-0.6
	비철금속	197(11.1)	223(12.2)	235(12.8)	1.8
화학소재	플라스틱	130(7.3)	151(8.3)	172(9.4)	2.8
	합성고무 및 케미컬	200(11.3)	211(11.5)	233(12.7)	1.5
유리 및 기타		79(4.4)	87(4.7)	84(4.6)	0.6
합계(차량무게)		1,778(100)	1,833(100)	1,833(100)	0.3

# 탄소섬유 강화 플라스틱(CFRP)



# AL vs Steel vs Ti vs Mg vs CFRP

Material	Price	Pot weight saving (vs. steel)	Use/applications	
Al	\$4-6/kg	20-45%	Hang ons, then moving into structure	Main materials for Auto BIW
Steel	\$1.3/kg	10%	Main structure, body shell, safety crash	
Ti	\$33-105/kg	50%	For rigidity parts low series	Limited use
Mg	\$13-26/kg	30-50%	Complex use with coating	
Carbon Fiber	\$52-105/kg	50%	Crash, high strength-rigidity, skin	Potential for future but price must come down





# Lexus LFA의 골격과 적용 소재

-  프리프레그
-  RTM
-  C-SMC \*1
-  알루미늄 합금
-  G-SMC \*2

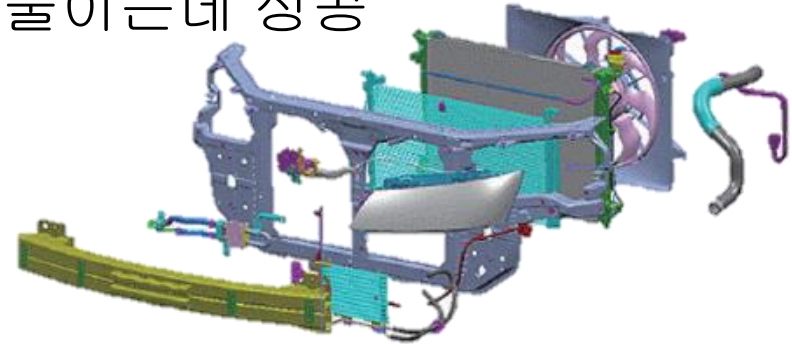


\*1 : Carbon-Sheet Molding Compound  
\*2 : Glass-Sheet Molding Compound

# AUDI A8의 FEM



PA6-GF30%(폴리아마이드 6에 glass fiber 30wt% 보강)를 활용하여 플라스틱과 금속을 결합한 하이브리드 기술로 이전 알루미늄 제품보다 무게를 약 20% 더 줄이는데 성공

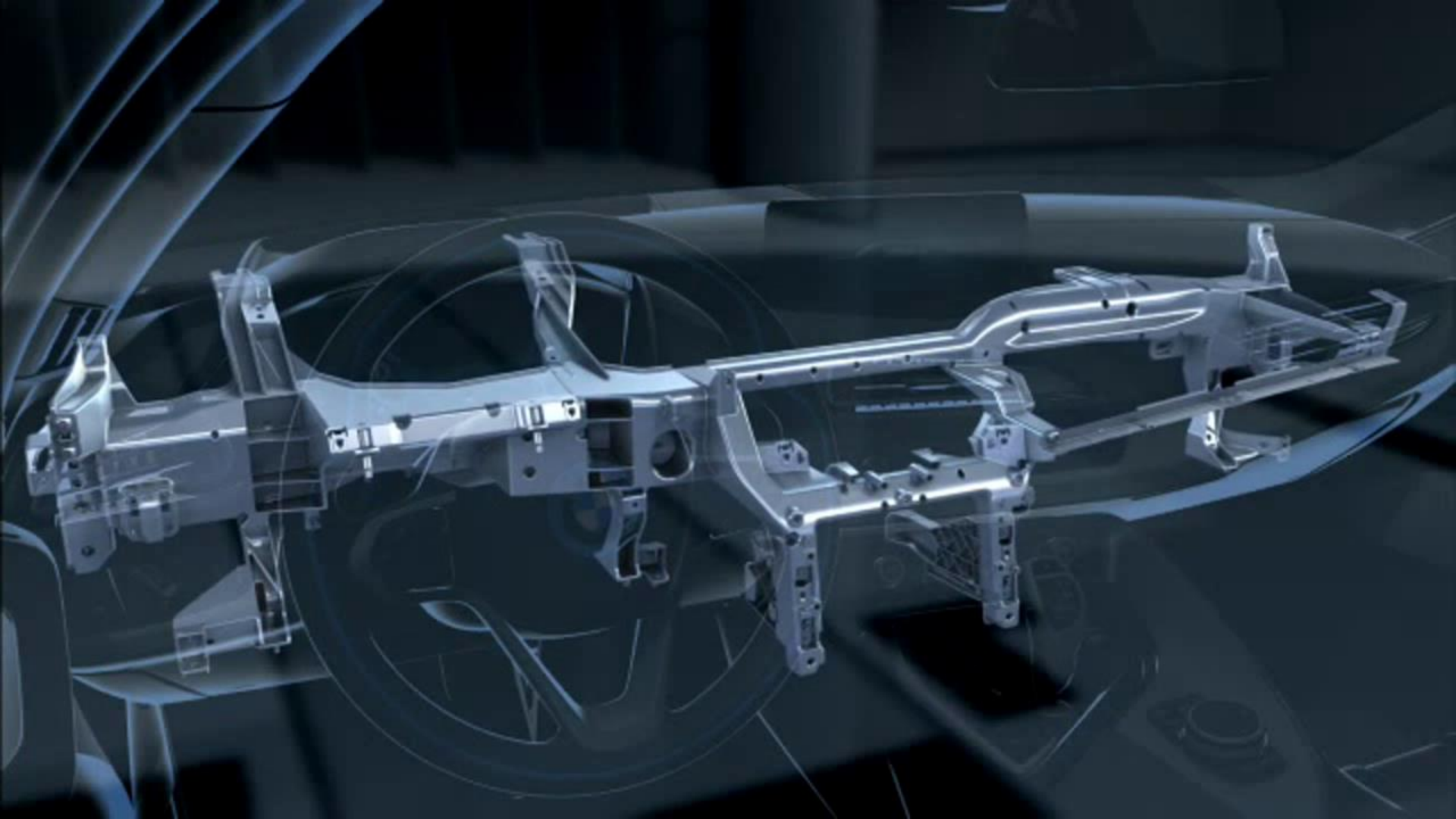










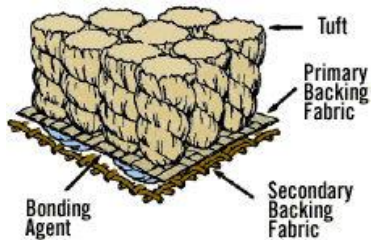


# 복합재(Composite)의 정의 - CFRP

- 정의: 복합 재료란 일반적으로 2종 이상의 다른 재료들로 만들어 지는 재료
- 정의에 따른 복합재의 예:
  - Steel (iron + carbon)
  - Carpet (backing fabric, yarn, glue, ...)
  - Duct tape (cloth + tape ...)



www.risleysteelservices.ca



www.carpets-rugs-guide.com



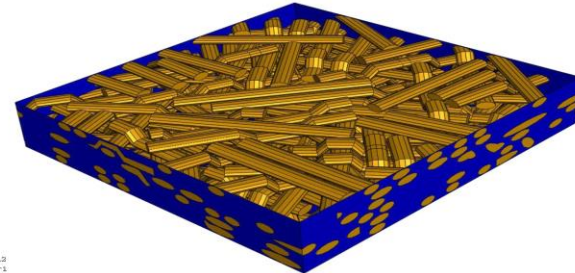
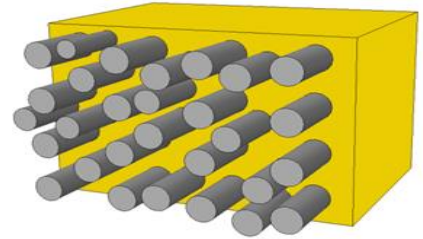
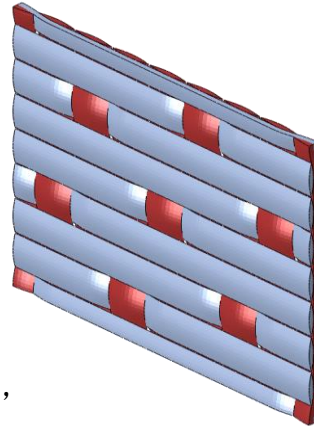
amazon.com

# 복합재(Composite)의 정의 - CFRP

- 엔지니어링 복합재의 정의:
  - 분명히 구별되는 서로 다른 재료 특성을 가진 2개 이상의 구성물로 이루어진 공학적 재료

## 구성:

- Fiber
  - Carbon, glass, Kevlar, ceramic
  - 강도와 강성을 제공
- Matrix
  - Thermoset, thermoplastic, metal, ceramic
  - Fibers를 지지하는 기능(fibers의 좌굴을 방지)
- Microstructure
  - Unidirectional, woven, chopped

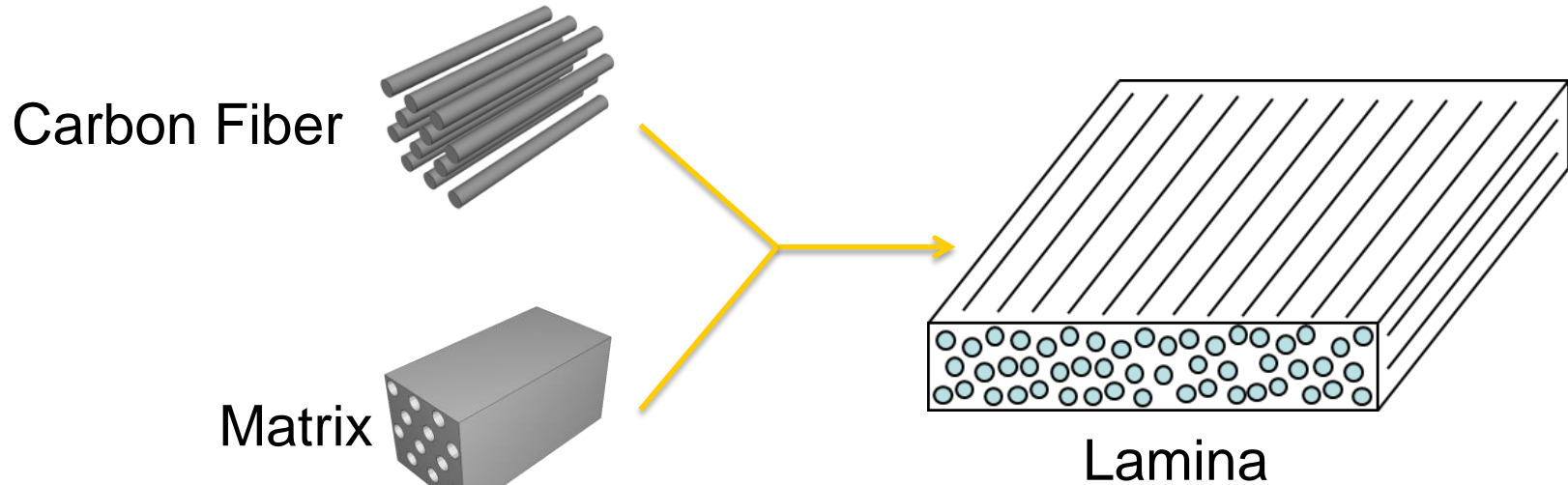


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# 복합재료 구조물 - Lamina

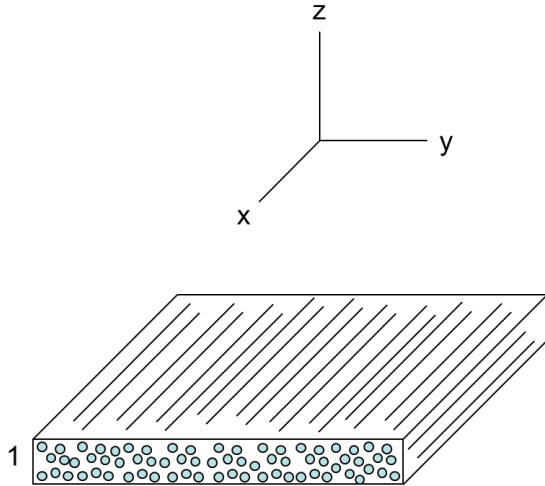
- Fiber와 matrix 재료로 각 **lamina** (ply) 블록을 제작



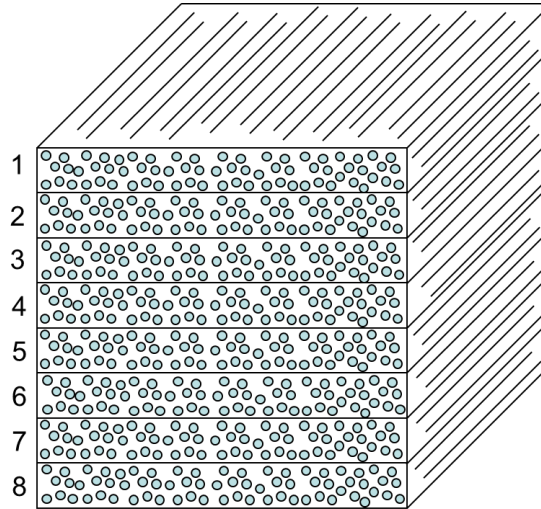
Fiber volume fraction: Lamina 속의 Fiber 의 부피 함량

# 복합재료 구조물- Laminate

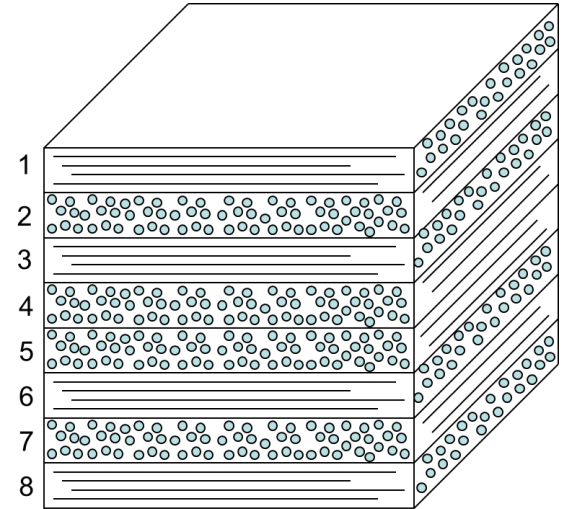
- 다양한 방향으로 Lamina들을 적층하여 **laminate**를 구성



Unidirectional lamina



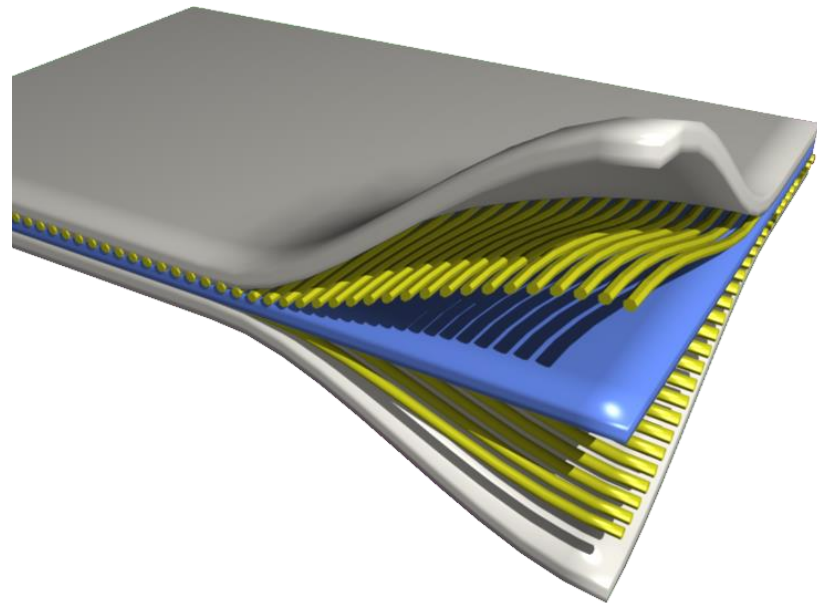
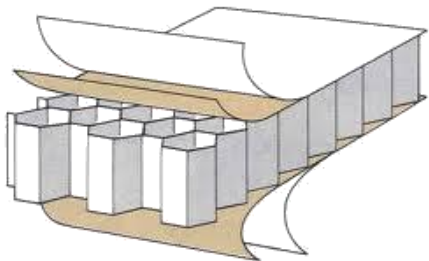
Unidirectional laminate



Cross-ply laminate

# Why Composites? | 재료 특성을 설계

- 재료의 배향성(Orientation)과 Plies의 적층 순서는 복합 소재의 재료 특성 응답을 설계하는 데 이용됨.
  - 탄성 거동 특성
  - 파괴 모드
  - 비선형 거동 특성
- 타 재료와 결합 가능성
  - Metal plies
  - Honeycomb plies (i.e. cores)



# Manufacturing Methods

- 다양한 제조 방법
  - 비용, 적용 제품, 재료 유형에 따라 선택
- 일반적 방법
  - Hand lay-up
  - Filament winding
  - Tape placement
  - Injection Molding
  - Compression Molding
  - Spray-up
  - Forming



gdecotech.com



compositesworld.com





# Injection Molding

- 절단된 fibers(short or long fibers)와 수지를 밀폐된 금형 내부로 사출
- 대량 생산 제품
- 상대적으로 작은 부품에 적용



zoltek.com

# Forming/Compression Molding

- Continuous fiber 또는 fiber 직조물을 수지와 함께 금형에 놓고 압력을 가해 성형
  - **RTM** - 수지에 압력을 가해 금형 내부로 사출
  - **VARTM** - 진공 금형 내부로 수지를 흡입
- Class A finish 제작 가능
- Cycle times이 짧음.

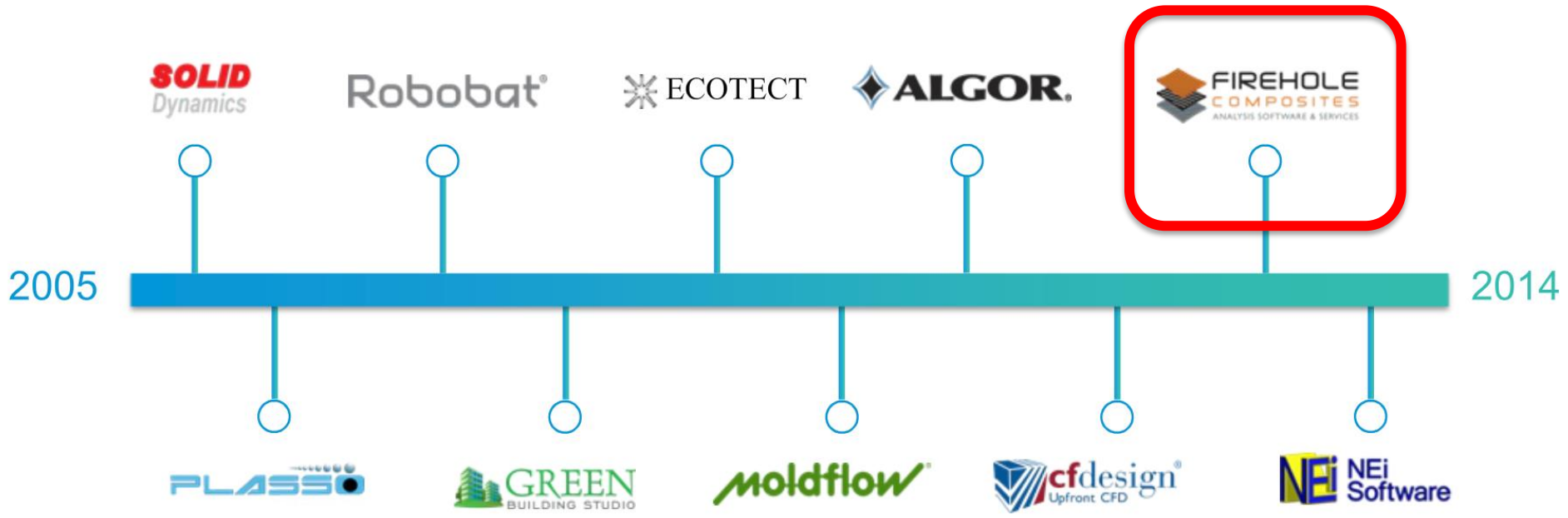


compositesworld.com



select-hydrofoils.com

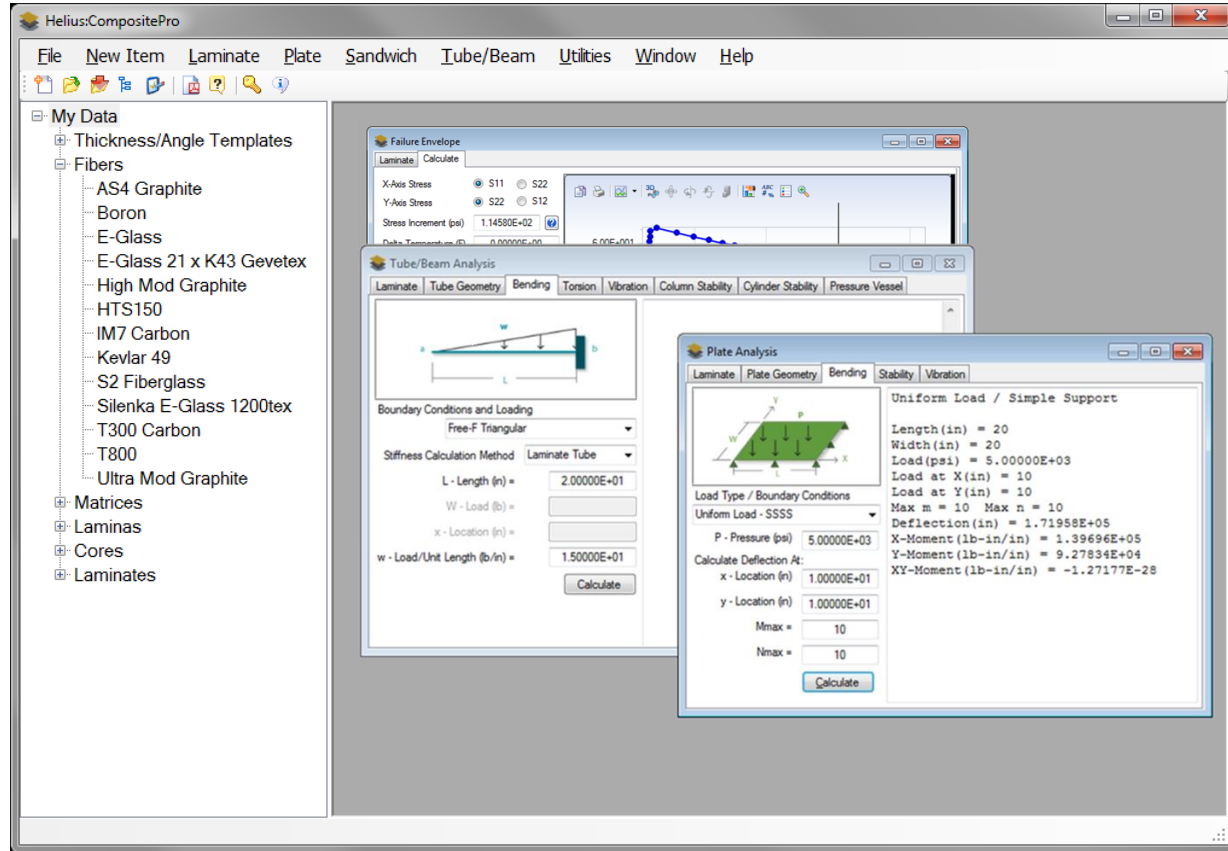
# Systematic Investments In Autodesk Simulation





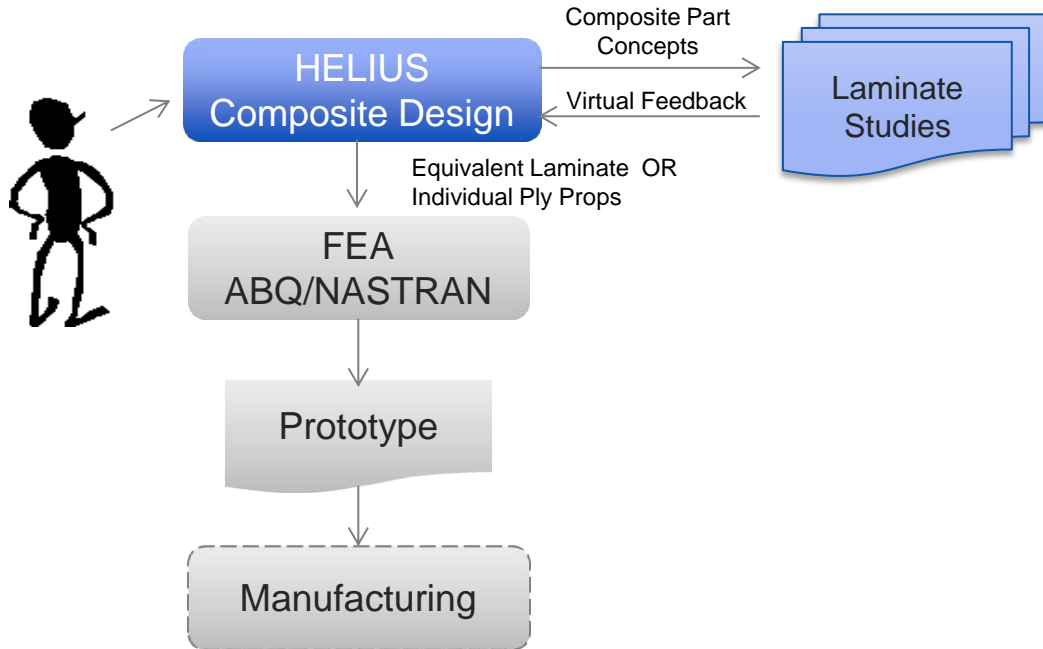
# HELIUS COMPOSITE

- ✓ 재료 DB / 재료 특성 분석
- ✓ 단순 형상의 구조 / 파괴 분석
- ✓ FEM PKG의 재료 특성 파일 생성
- ✓ ...And much more





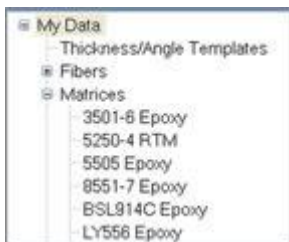
# HELIUS COMPOSITE



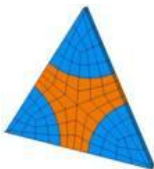


# Material Analysis

Material Library:



Lamina from Micro Mechanics:



Input Fiber/Matrix, Lamina and/or Laminate data

# Laminate Analysis

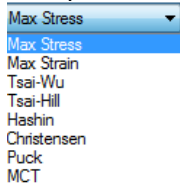
Equivalent Laminate Props:

Title	Value
Ex (psi)	1.32512E+07
Ey (psi)	1.76764E+07
Ez (psi)	9.16388E+06
Gxy (psi)	3.28911E+06
Gxz (psi)	3.17308E+06
Gyz (psi)	3.23109E+06
NUxy	1.58603E-01
NUyx	2.11567E-01
NUxz	3.93142E-01
NUzx	2.71878E-01
NUyz	3.67837E-01

Laminate Response

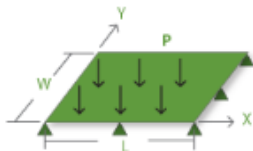
Factor of Safety

Composite Failure

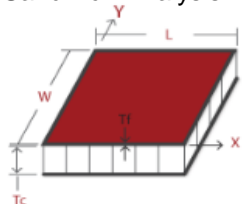


# Simple Structural Analysis

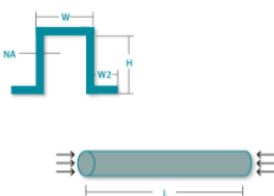
Plate Analysis:



Sandwich Analysis:



Beam/Tube Analysis:

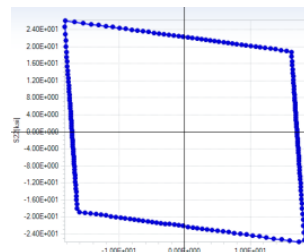


# Advanced Laminate Analysis

Progressive Failure:

Inc	SDMAn (psi)	SDMMy (psi)	SDMMyz (psi)	EPSILON (in/in)	EPS
1	2.0000E+03	-1.95431E-13	0.0000E+00	1.54779E-04	2
2	4.0000E+03	-3.10862E-13	0.0000E+00	3.09557E-04	4
3	6.0000E+03	-3.9960E-13	0.0000E+00	4.64335E-04	6
4	8.0000E+03	-4.21726E-13	0.0000E+00	6.19114E-04	8
5	1.0000E+04	-5.32907E-13	9.9607E-30	7.73892E-04	-1
6	1.2000E+04	-6.32907E-13	4.9302E-30	9.28671E-04	-1
7	1.4000E+04	-3.95271E-13	9.9607E-30	1.08345E-03	-1
8	1.6000E+04	-1.98872E-12	9.9607E-30	1.23823E-03	-1
9	1.8000E+04	-2.99705E-13	6.16298E-31	1.42417E-03	4
10	2.0000E+04	-6.95112E-13	-3.3894E-30	1.58241E-03	-5

Failure Envelopes:

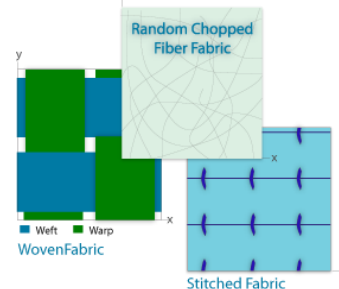


# Utilities

Export Lamina/Laminate to FEA:

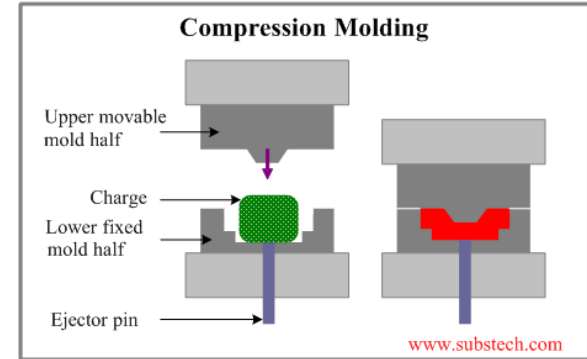
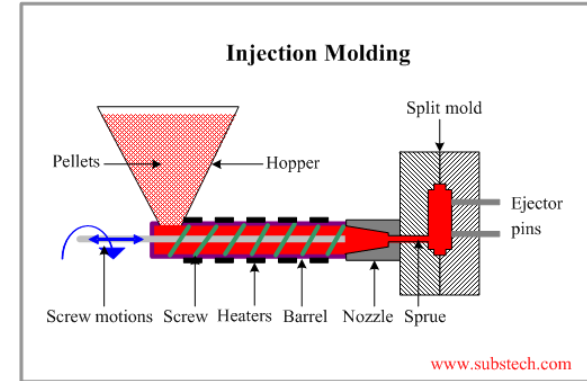
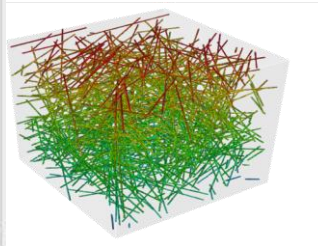
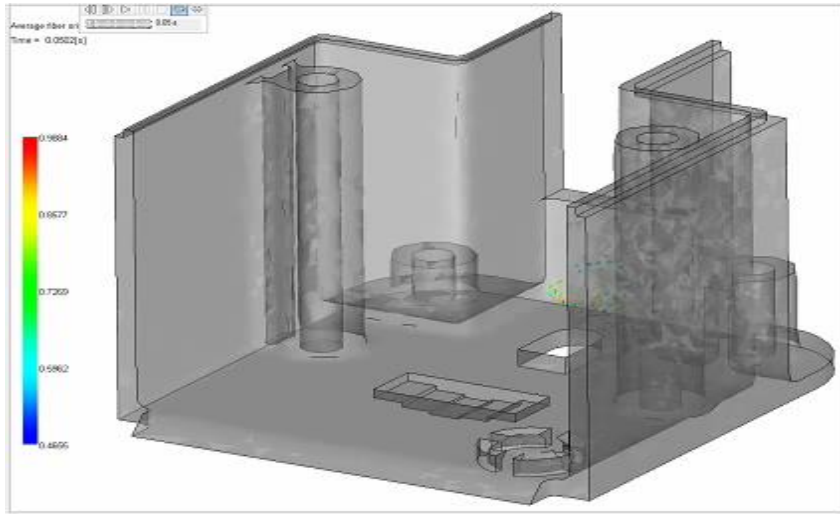


Fabric Builder:





- Injection Molding
- Compression Molding



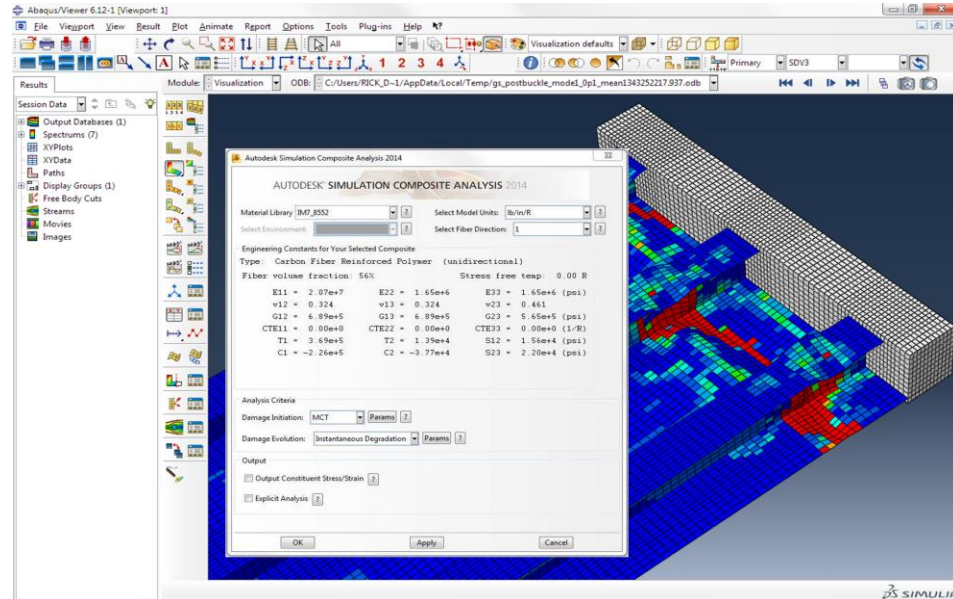


## Composites Simulation Platform

기존 CAE Packages  
(Abaqus/ANSYS/Nastran)를  
복합재에 특화된 Solution으로 향상

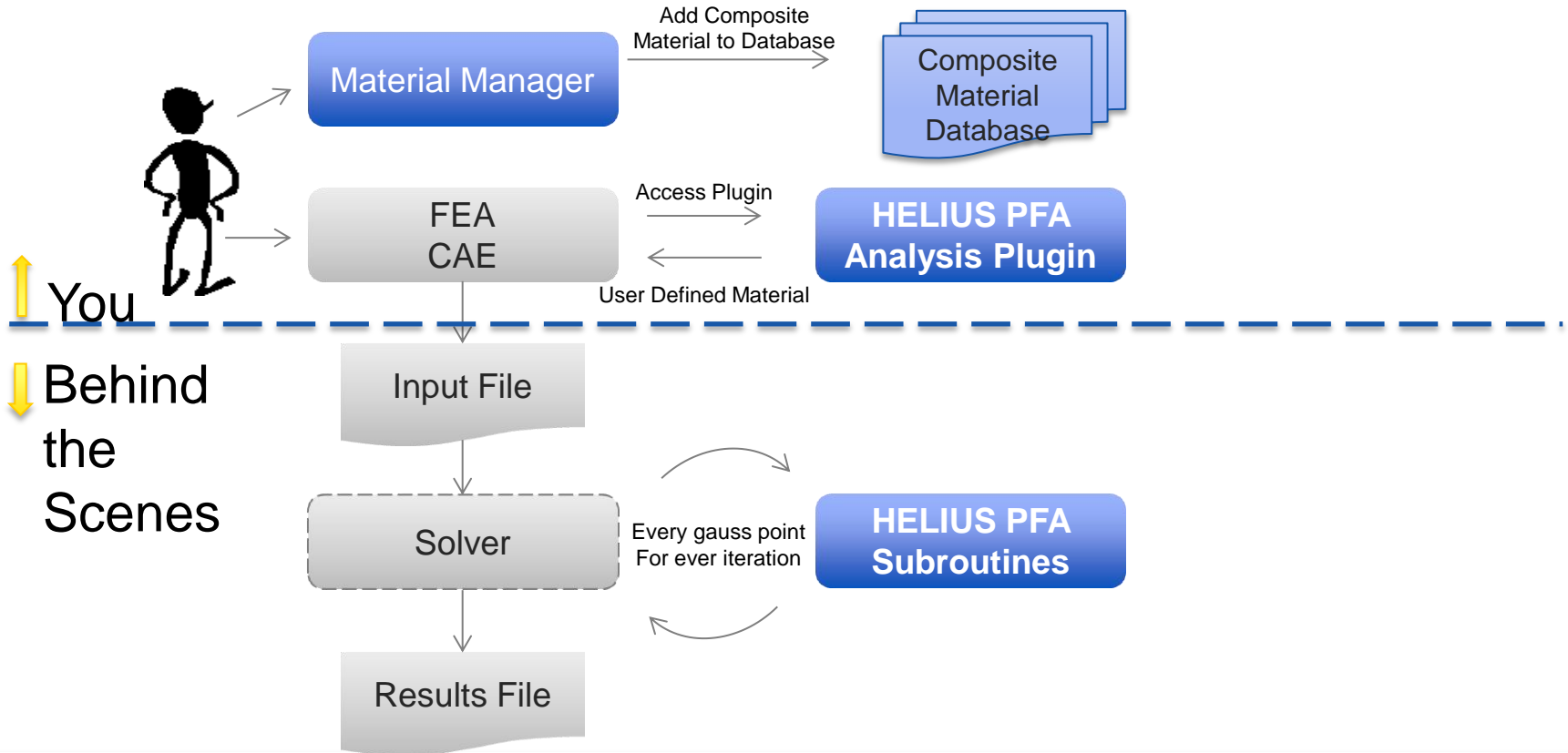
좀더 사실적인 데미지를 고려한  
비선형 복합재 해석

빨리 익히고 쉽게 사용할 수 있는  
구성





# HELIOUS PFA

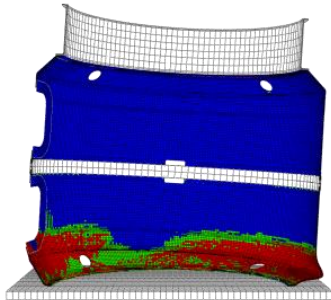




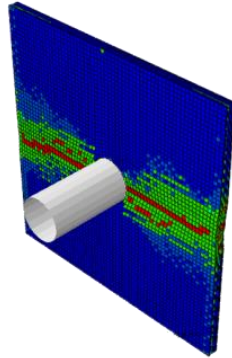
# HELIOUS PFA



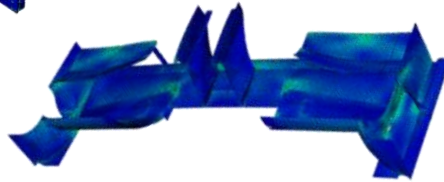
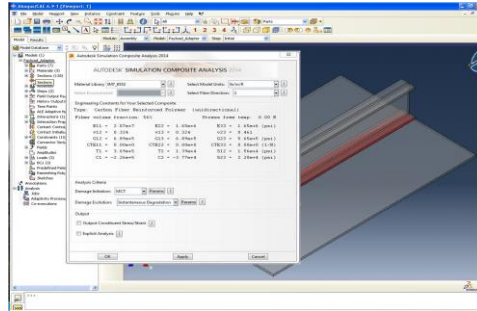
재료 테스트  
회수 감소



사실적인 데미지 시뮬레이션  
(**damage simulation**)을 통해 위험  
요소 감소



개발 주기 초기 단계에서 설계 개선



복합재 설계와 해석을 위한  
학습 시간 단축



설계 주기 단축

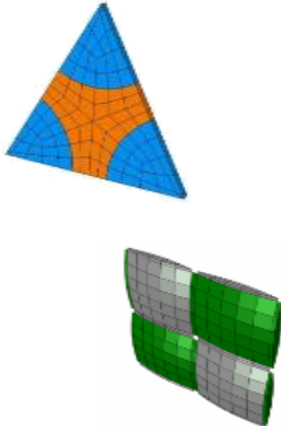
## 복합재를 이용한 **Simulation** 기회 공급



# Material Management

Characterized constituent behavior from lamina inputs:

- Uses an iterative micromechanics based solver to calculate “in-situ” properties.
- Calculates constituent nonlinearity from lamina inputs.

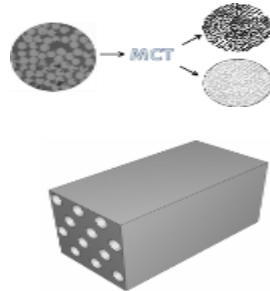


# Multi-scale Analysis

Multiscale analysis allows constitutive relationship to be applied where they are most accurate, at the constituent level, rather than the homogenized lamina level.

Microstructural support for:

- Unidirectional
- Plain Weave
- 5H Satin Weave
- 8H Satin Weave
- Delamination



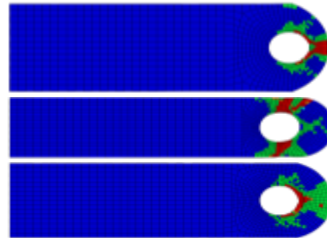
# Failure, Damage & Fatigue

Eight failure criteria offered:

- MCT
- Hashin
- Puck
- Christensen
- Tsai-Wu
- Tsai-Hill
- Max Stress
- Max Strain

Models for damage tolerance & delamination.

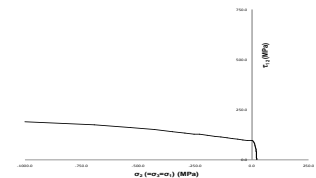
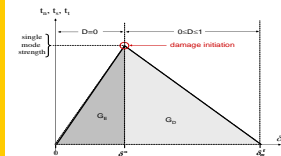
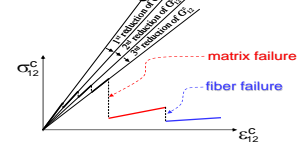
$$\pm A_1^f (I_1^f)^2 + A_4^f I_4^f = 1$$



# Material Nonlinearity

Material nonlinearity is Heliu:MCT's specialty:

- Robust algorithms to greatly improve convergence
- Multiple material models
  - Brittle unload
  - Strain softening
  - Crack accumulation
  - Ductile softening



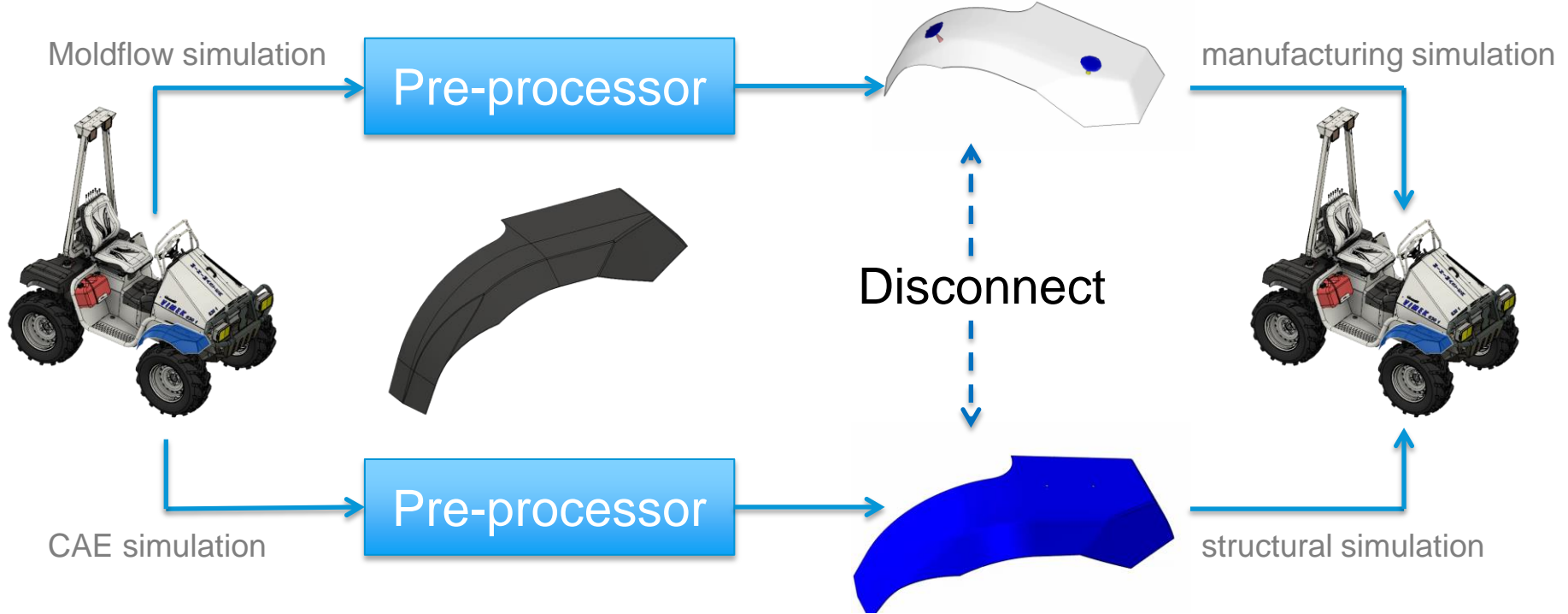


# Autodesk® Helius PFA (Composite Analysis) Advanced Material Exchange

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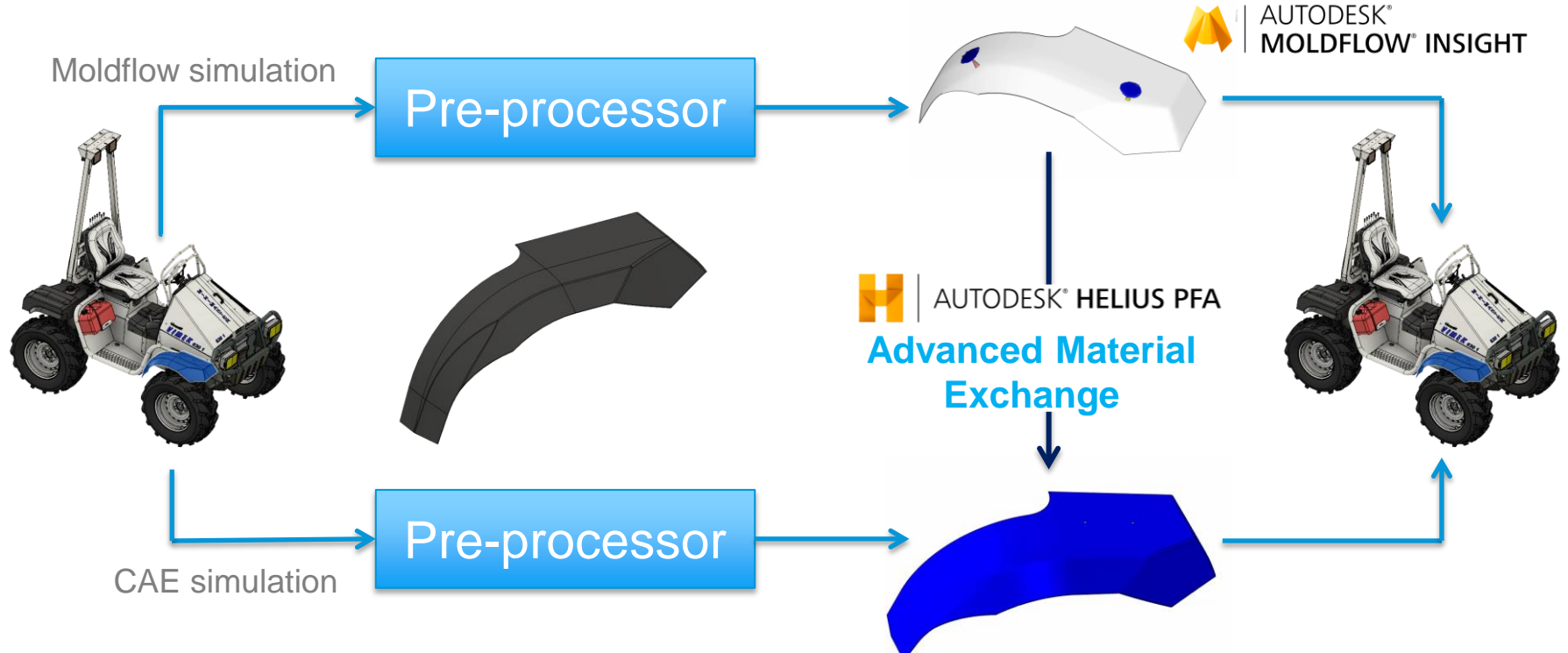
**AUTODESK**

# Typical workflow



# Advanced Material Exchange

## As-manufactured simulation



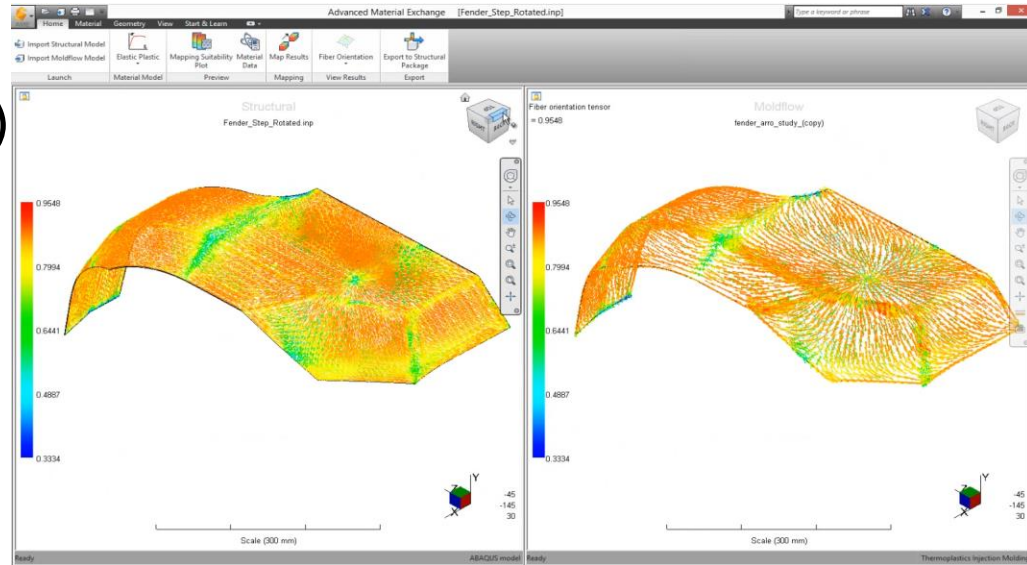
# Advanced Material Exchange capabilities

Map data from Moldflow to Abaqus & ANSYS

- Material properties
- Fiber orientations
- Residual strains (warpage)

Supported materials

- Non-filled plastics
- Fiber-filled plastics



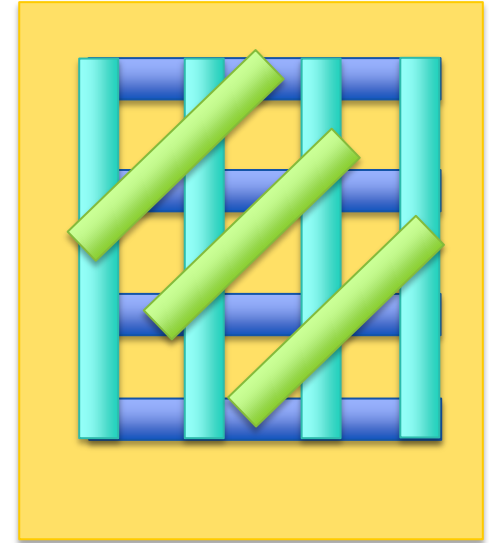
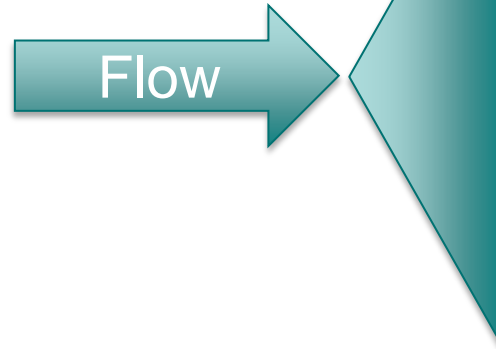
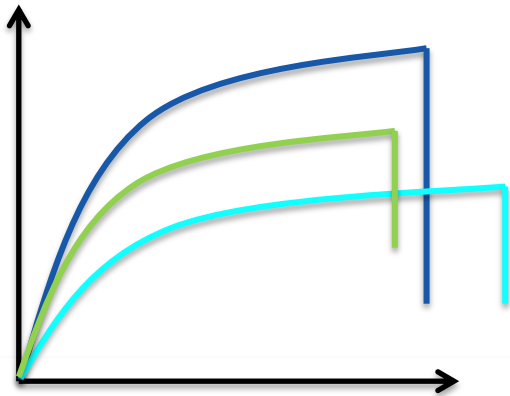
Results in a more realistic model of the part—  
thus a more accurate structural analysis.



# Advanced Material Exchange

## Requirements

- Simulation Moldflow Insight Premium
- Abaqus 6.12 – 6.14
- Stress-Strain Curves
  - Nonlinear to failure
  - Chopped fiber only



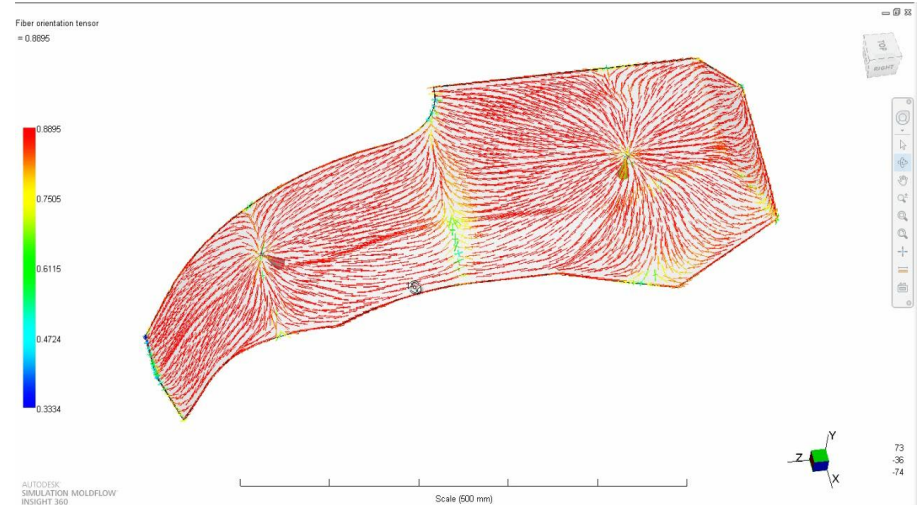
# Chopped fiber microstructures

Coupled with advanced material exchange

- Use fiber orientations in your simulation

Nonlinear FEA simulation

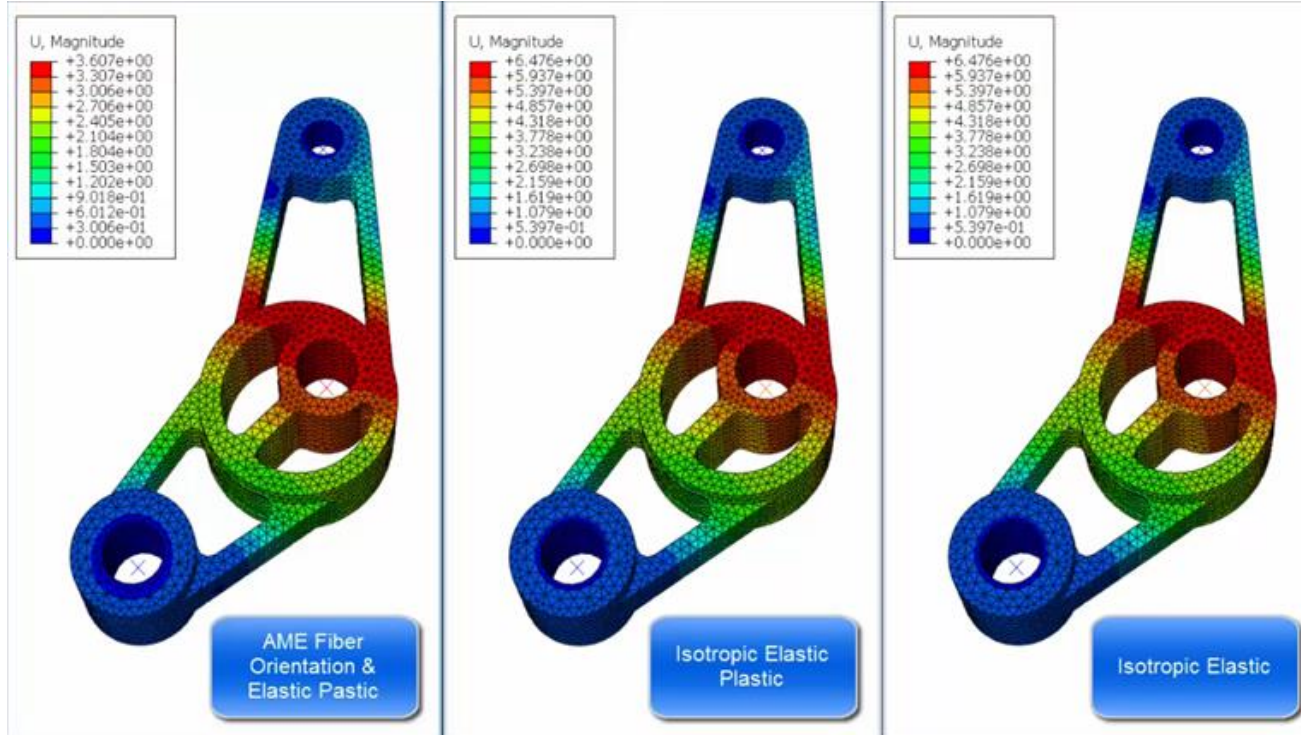
- Elastic-plastic response
- Failure predictions



# Perform as-manufactured simulations

The as-manufactured simulation provides better insights into actual product performance.

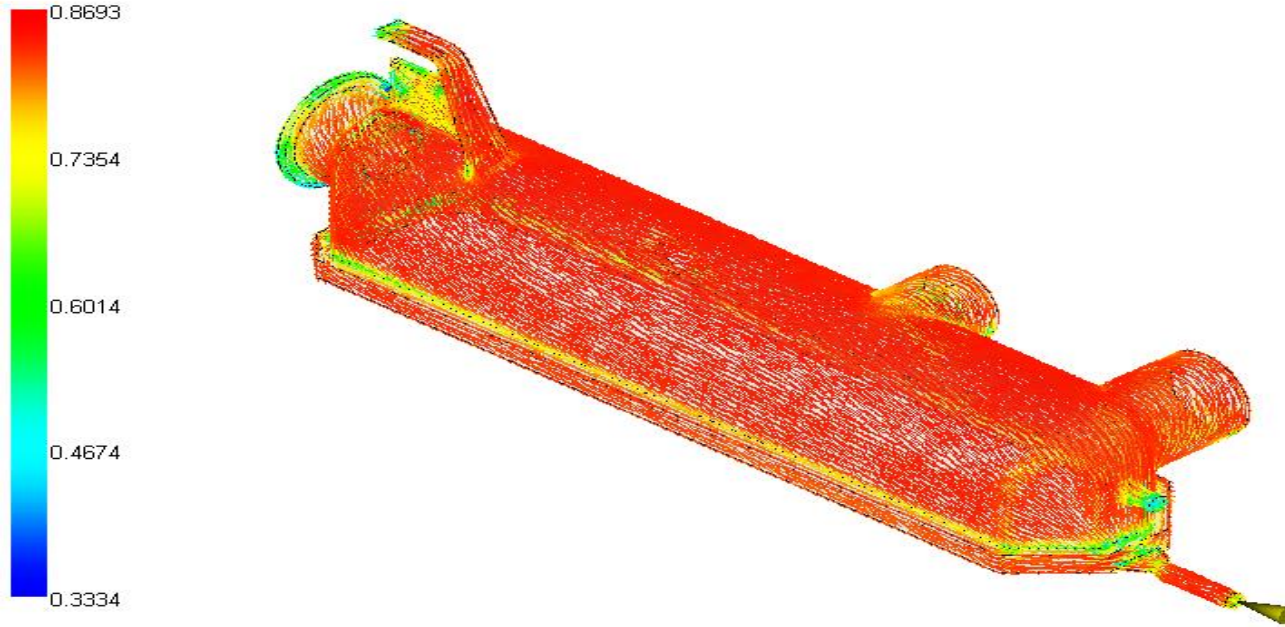
In this case—half the deflection of an isotropic model



## Example – Effect of change in gate location

- Two models that are exactly the same
  - Geometry
  - Materials
  - Loads
- Difference is the gate location.
  - One on top of the part, one at the front.
- Examine the difference in strain due to the difference in fiber orientations.

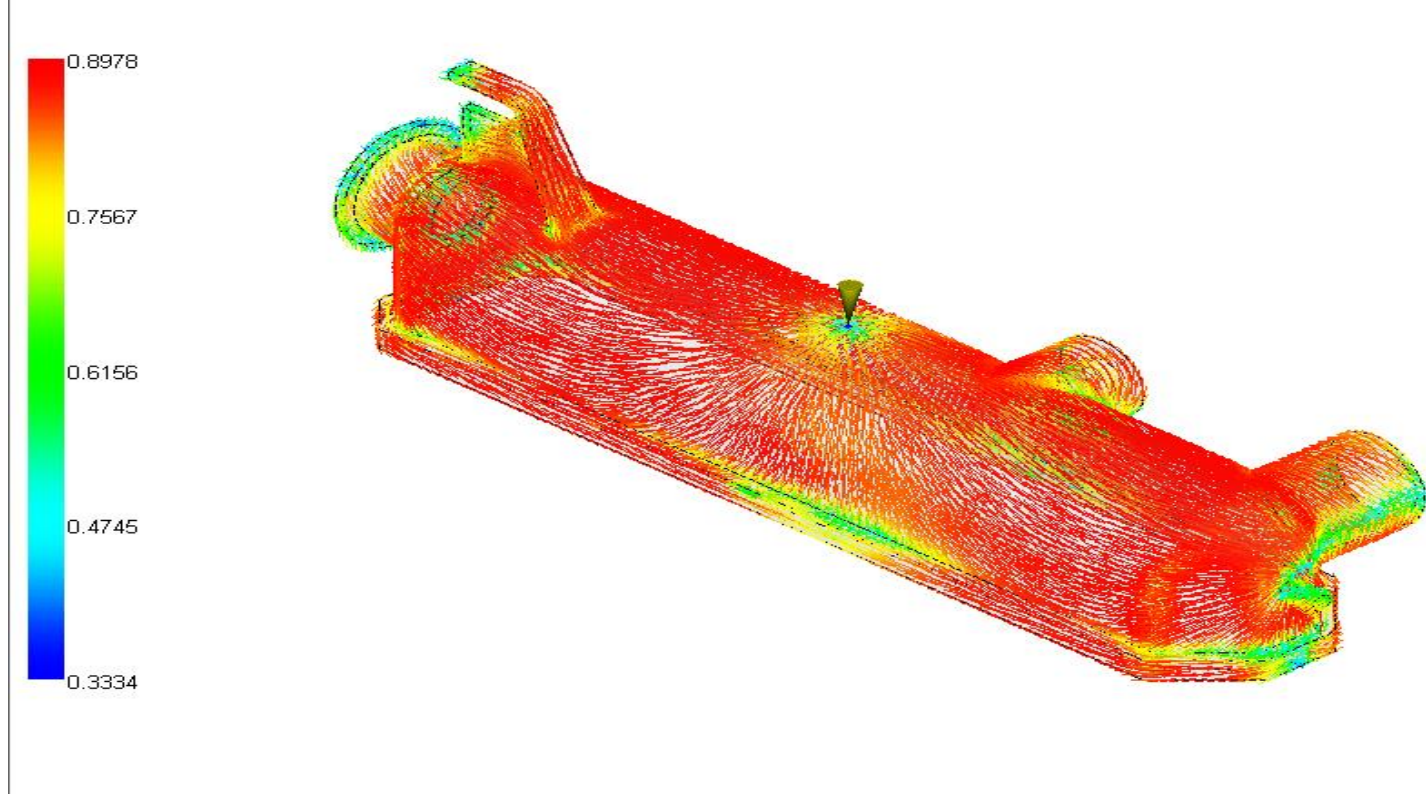
# Example – Effect of change in gate location



Front Gate Location

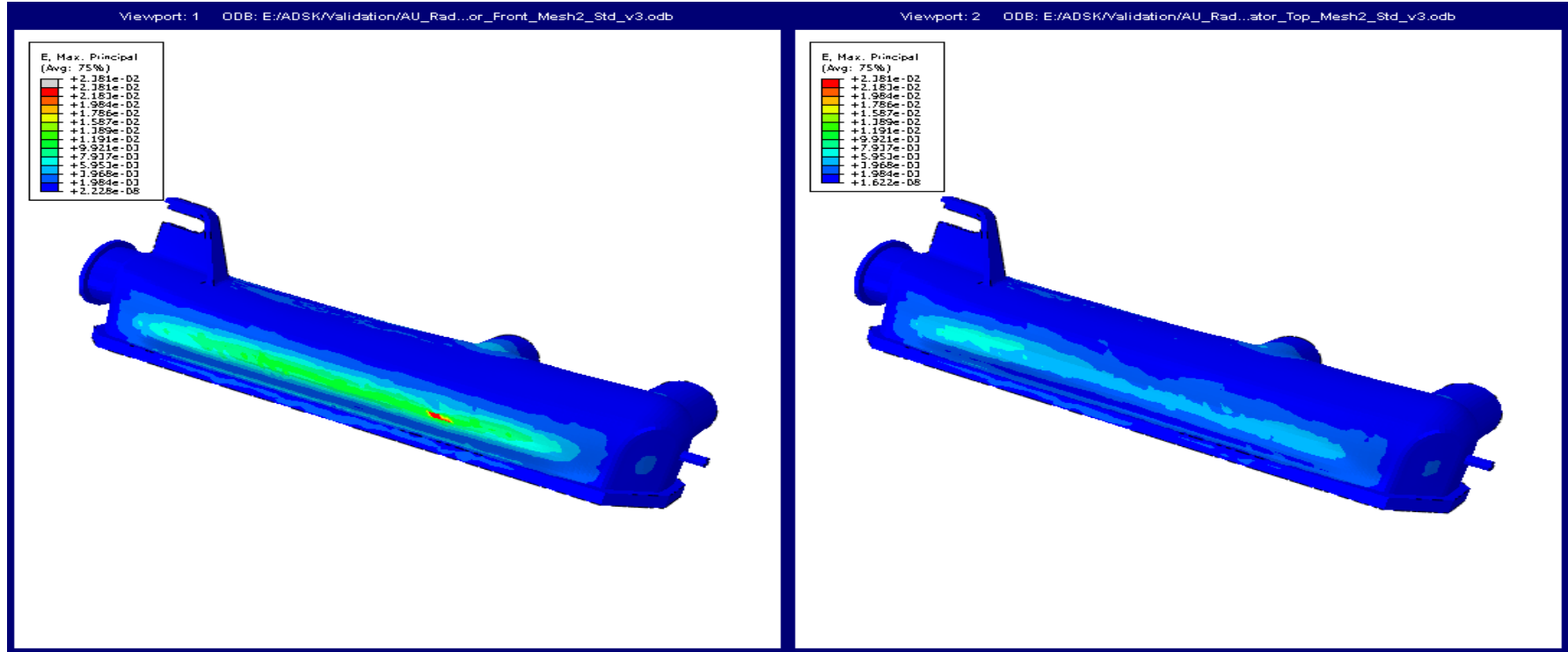


# Example – Effect of change in gate location



Top Gate Location

# Effect of changing gate location



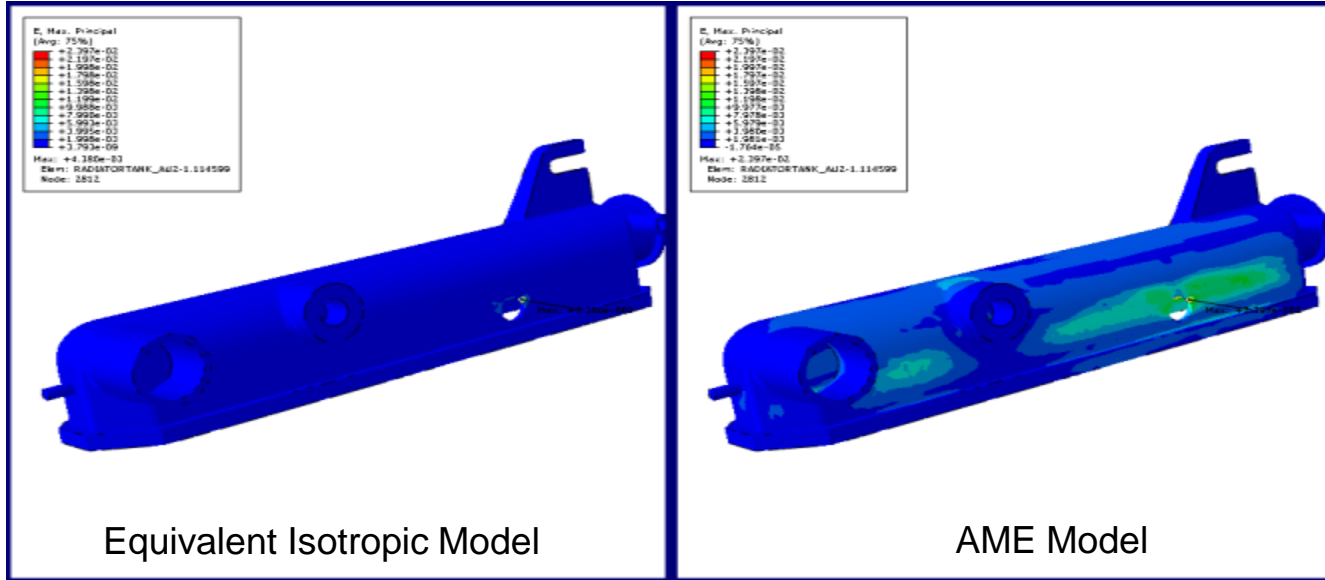
Front Gate Location

Top Gate Location

# Comparison to Linear Analysis

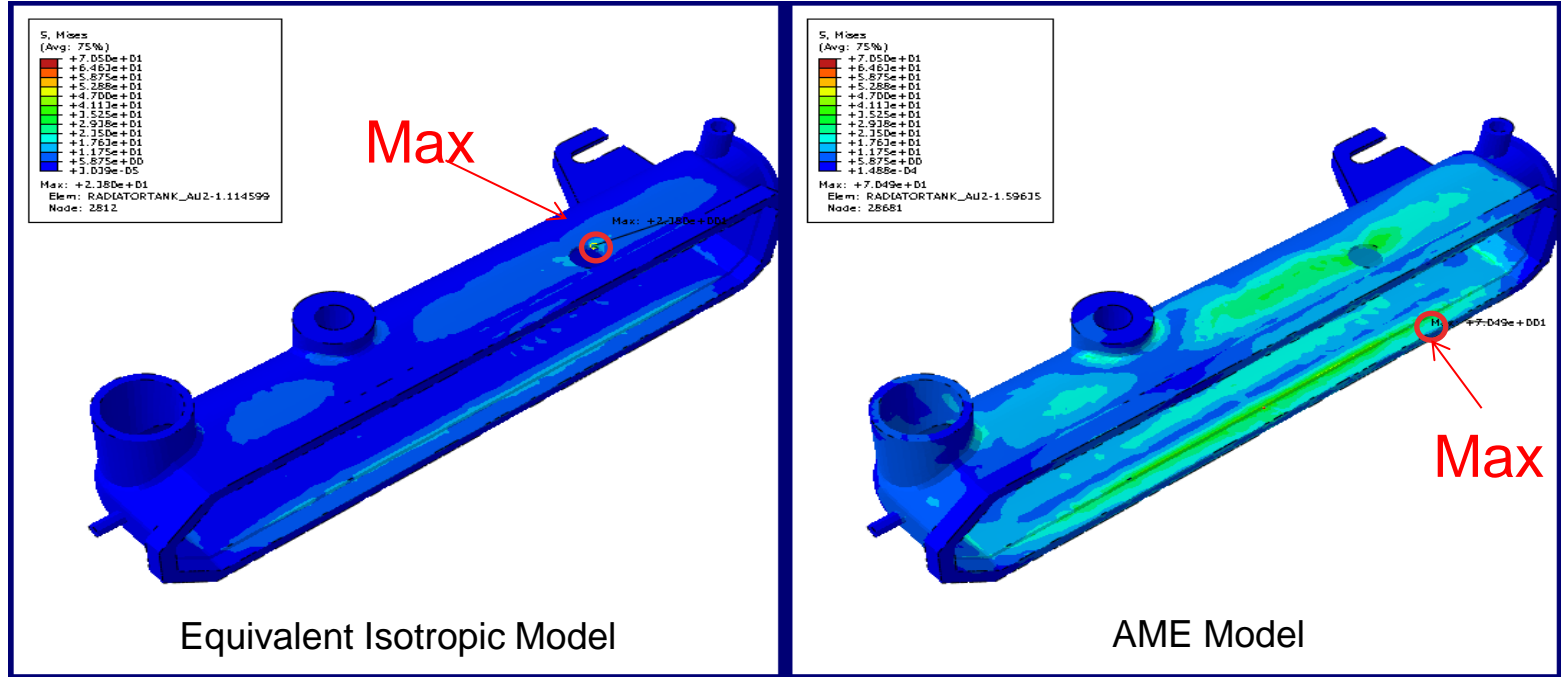
- Linear Equivalent Analysis
  - Ignores the effects of fiber orientation – using an “equivalent” isotropic material representation.
  - Ignores nonlinear material behavior.
- AME Model
  - Accounts for the effects of fiber orientation
  - Accounts for nonlinear material behavior.
- Models shown at the same pressure load

# Results Comparison – Max Principle Strain



- The AME Model predicts  $\sim 5.5x$  higher max principal strain

# Results Comparison – Composite von Mises stress



The AME model predicts a 3x higher von Mises stress. It also occurs at a different location than in the equivalent isotropic model.





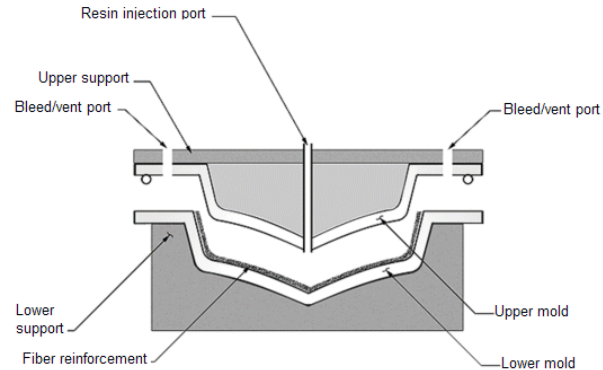
# Autodesk® Moldflow RTM Process (CFRP Molding Process)

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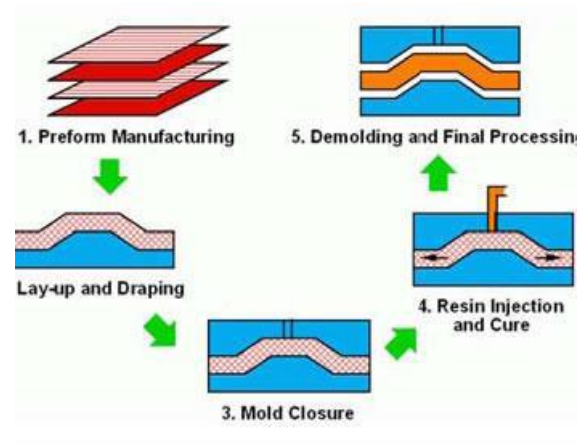
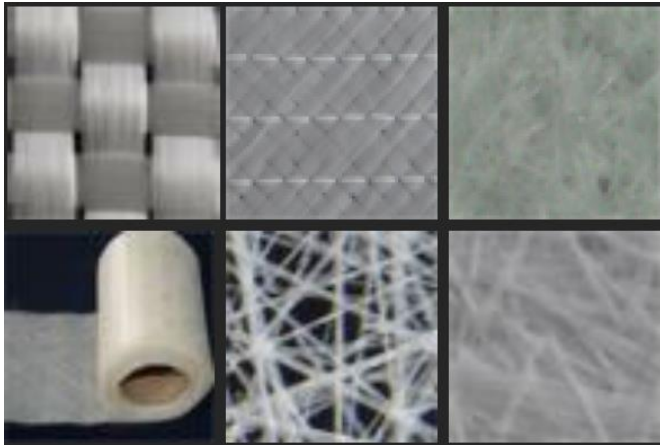
# RTM, Resin Transfer Molding

is a low pressure, closed molding process which offers a dimensionally accurate and high quality surface finish composite molding, using **liquid thermoset** polymers reinforced with various forms of **fiber reinforcements**.



# RTM Process

Reinforcements are presented in their dry form to the mold in either binder-bound chopped mat, random-continuous strand mat or woven cloth format. The fiber has been either "preformed" to the exact shape of the molding tool in a previous operation or is hand-tailored during the loading process in the molding tool.



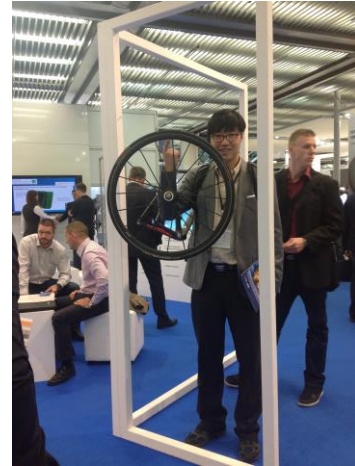
# RTM Process

Premixed catalyst and resin is injected into the mold cavity encapsulating the fiber within. The primary surface of the molding may be gel-coated, a process of spraying the mold surface before installing the fiber. If a gel coat is not required, the exterior finish would be the same from the front to back of the molded part.



# RTM Applications

Parts for high strength, high modulus.  
Parts for dimensional stability and good surface.

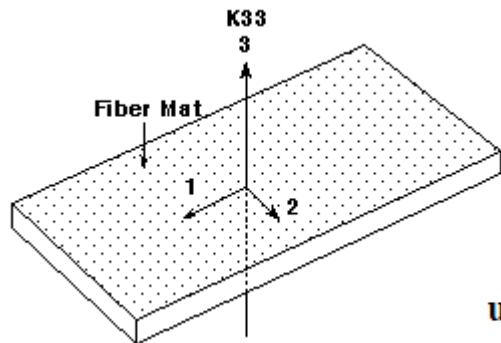
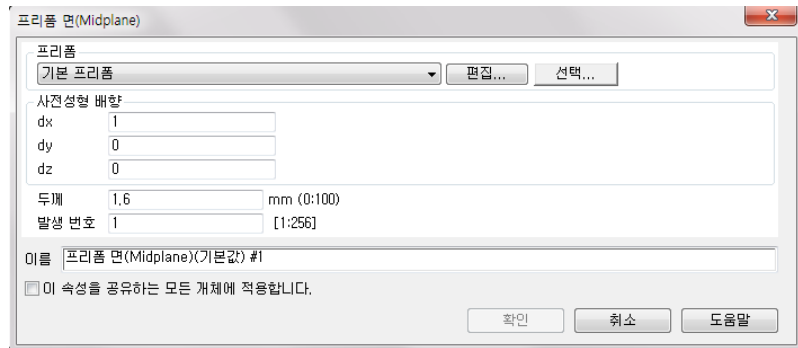


# Preform Properties

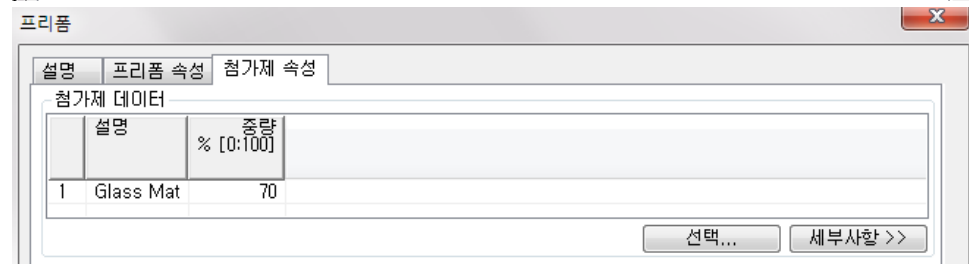
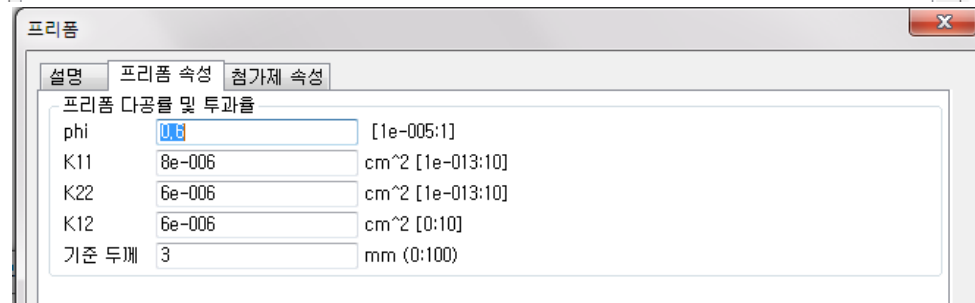
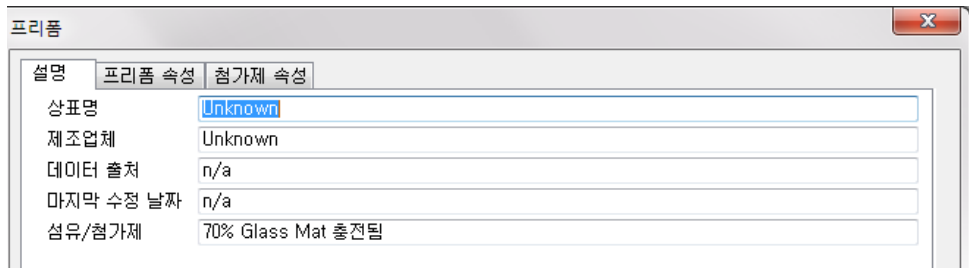
- The type of flow is characterized by preform(carbon nanotube mat) properties. Flow resistance also depends on resin property and flow rate(molding conditions)
- **1. Porosity (다공율 or 기공율)** is defined as the ratio of the void volume to the cavity volume, before the cavity is filled with resin For different type of mat layers
- **2. Permeability (투과성 or 삼투성)** is part of the proportionality constant in Darcy's law which relates discharge (flow rate) and resin properties (e.g. Viscosity), to a pressure gradient applied to the porous media.



# Preform Properties



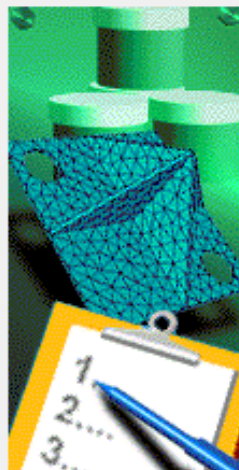
$$u = -\frac{1}{\eta} \mathbf{K} \cdot \nabla P$$



Porosity(다공률), permeability(투과율) and reference thickness(기준두께)

# Process setting

공정 설정 마법사 - RTM/SRIM 설정 - 페이지 1/2



금형 표면 온도	<input type="text" value="100.1"/>	C
용융 온도	<input type="text" value="30"/>	C
공칭 사출 시간	<input type="text" value="5"/>	s [0:300]
용융 초기 변환	<input type="text" value="0"/>	[-1:1]
경화 시간	<input type="text" value="30"/>	s [0:]
사출기 압력 한계		
최대 사출기 유압	에서 <input type="text" value="0.1"/>	MPa [0:50]
인텐시피케이션 비	<input type="text" value="10"/>	(0:30)
사전 조절 해석		
사전 조절 분석 수행	<input type="button" value="데이터 편집..."/>	

< 뒤로(B)

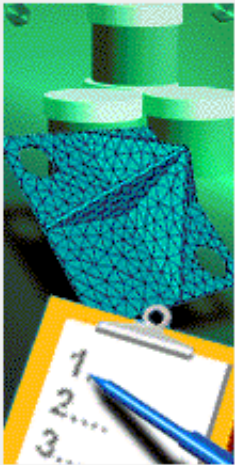
다음(N) >

취소

도움말

# Process setting

공정 설정 마법사 - 프로파일 설정 - 페이지 2/2



**%램 속도 대 %스트로크**

	%스트로크 % [0:100]	%램 속도 % (0:100)
1	100	100
2	0	100
3		

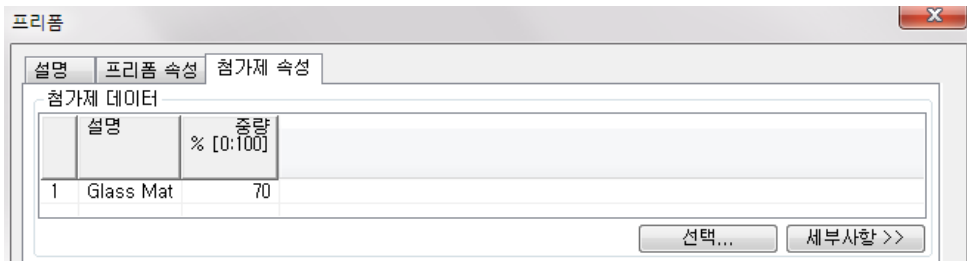
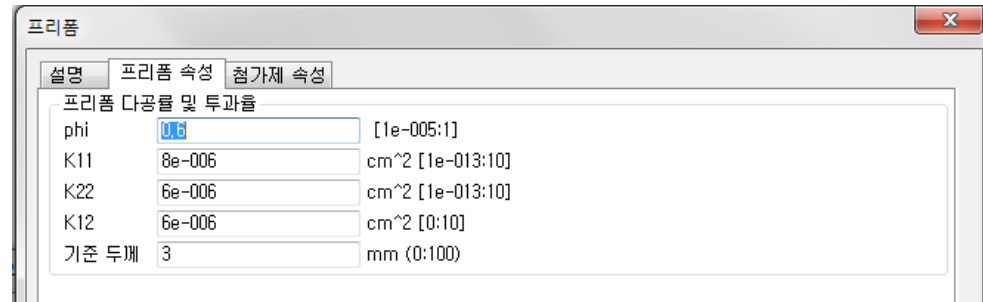
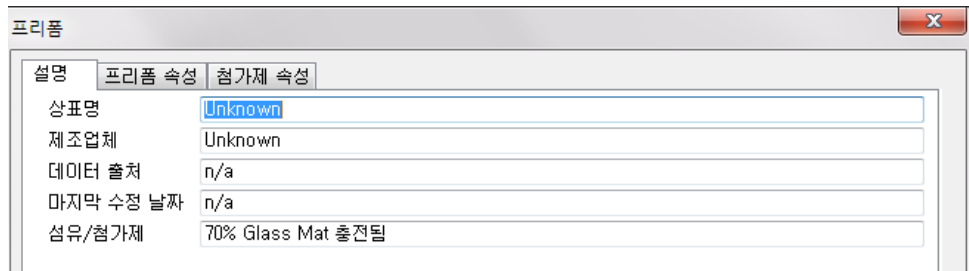
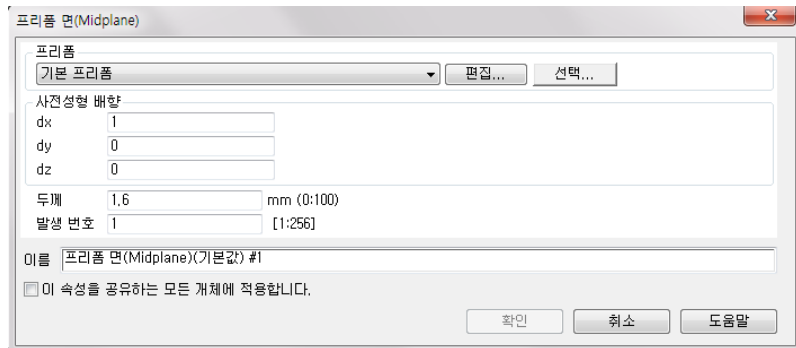
먼저 도래하는 것에 따른 보압 전환

%충전 체적에 따른      에서 99      % [0:100]

사출압에 따른

압력 제어점에 따른

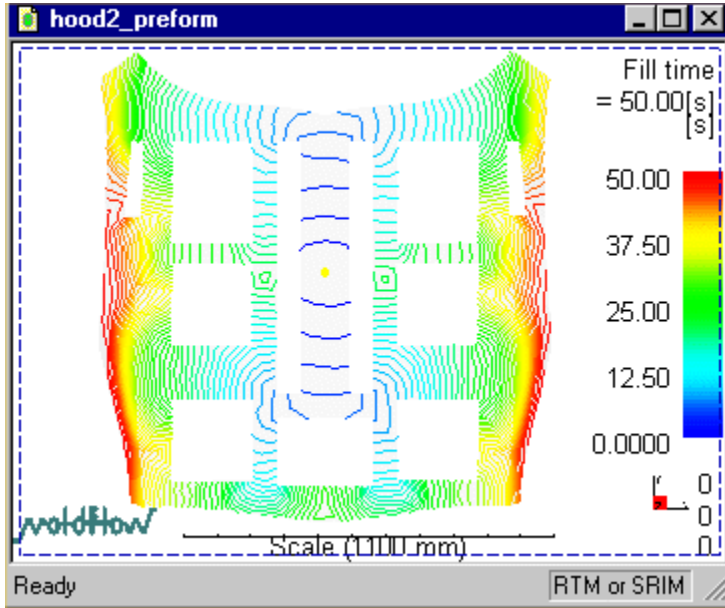
# Process setting



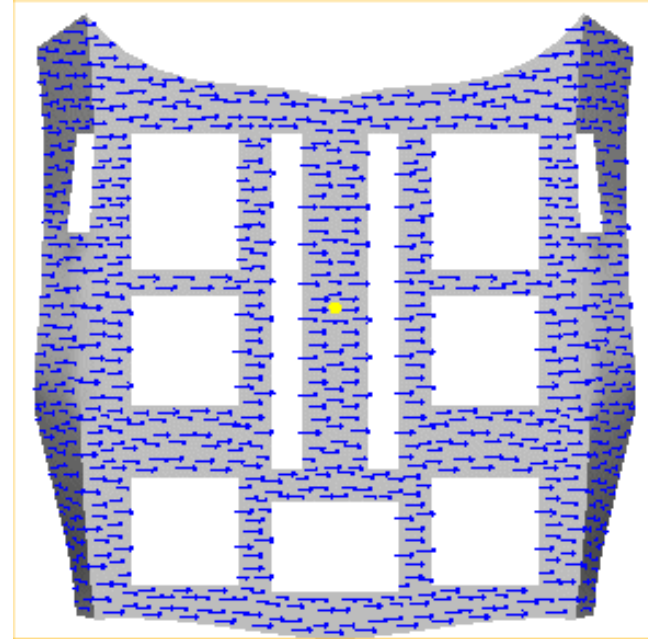
# Process setting



# Simulation Example



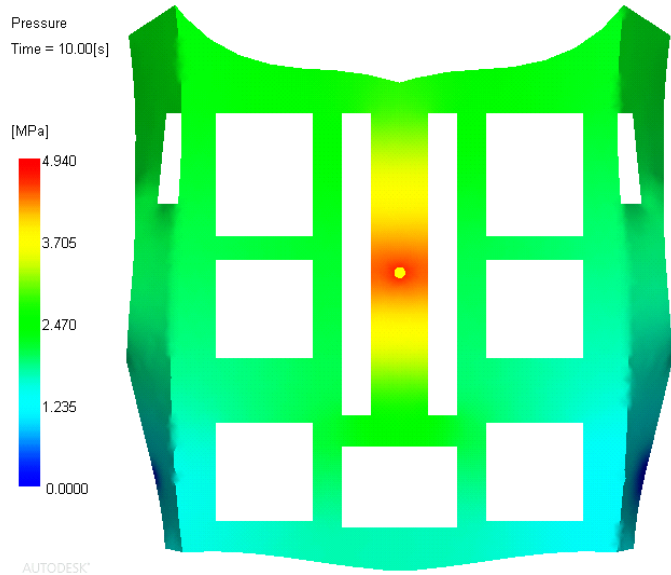
Fill pattern



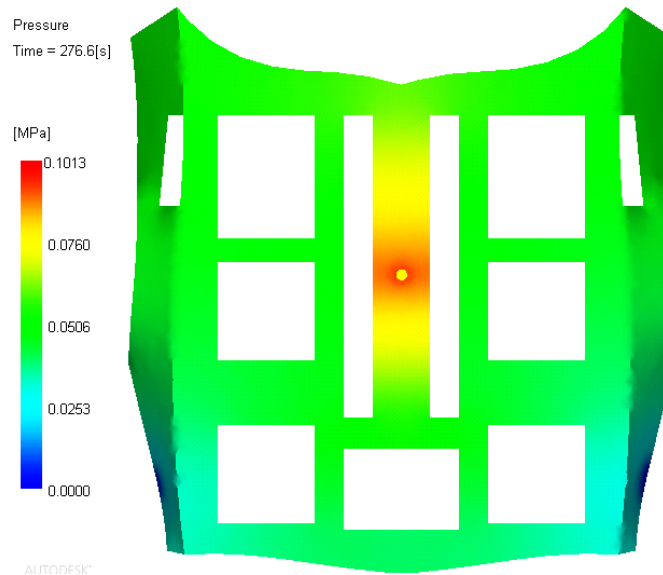
Preform orientation



# VARTM (Vacuum Assisted Resin Transfer Molding)



**RTM**



**VARTM**



# Autodesk® Moldflow Mucell Process (Microcellular Molding Process)

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# Simulation of the MuCell® Microcellular Foaming Process in AMI 2016

Levi Kishbaugh

VP Engineering – Trexel, Inc.  
Corporation

Sejin Han Tim Lankisch

Autodesk

Director of Engineering – CAE Services

# Class summary

이 시간에는 미세 발포 성형 공정의 기본과

일반 사출과의 주요 차이점을 설명하고,

Moldflow Insight 의 Mucell 해석을 통해 얻을 수 있는 이점에 대하여 설명하겠습니다.

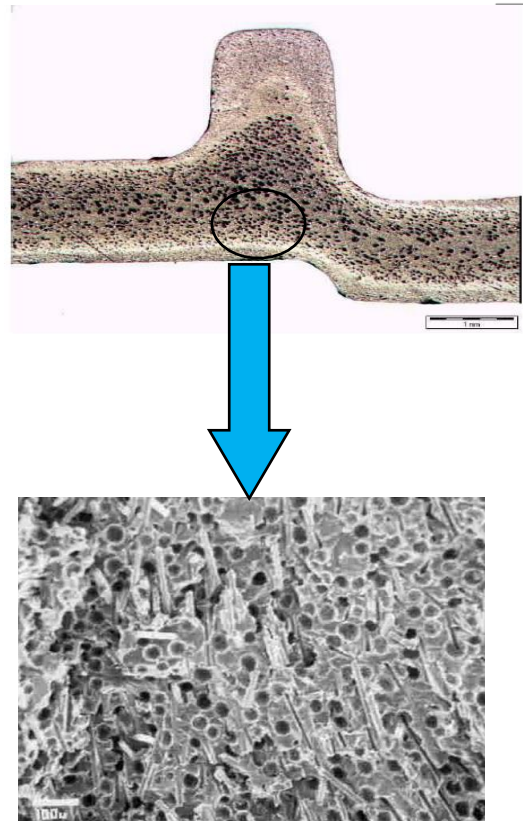
# Key learning objectives

이시간 후에는 아래 사항을 이해할 수 있습니다 :

- MuCell® 미세 발포 사출 성형 공정의 기본적인 역학
- 미세 발포 성형과 일반 사출 성형 사이의 주요 차이점
- 기포 핵 생성 및 셀 성장과 관련된 시뮬레이션 문제
- 미세 발포 사출 성형 시뮬레이션을 위한 개선된 Moldflow

# What is MuCell®?

- MuCell은 포밍 테크놀러지
  - 플라스틱 제품에 작은 셀(기포)을 넣는 기술
- 발포제(foaming agent)로는 주로 질소를 사용
  - 때때로 이산화탄소 사용

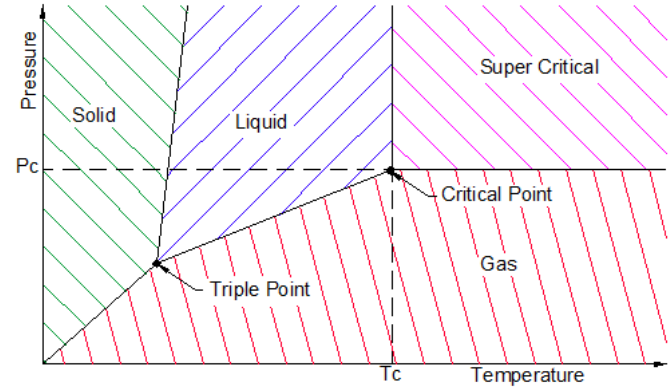




# Gas 용해 (Single Phase Solution 만들기)

## ■ Single Phase Solution 만들기

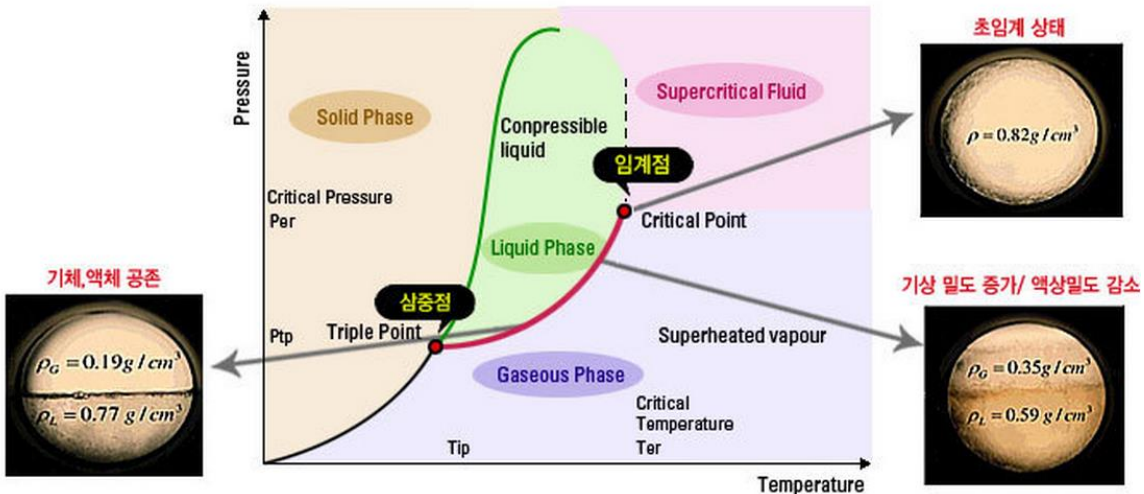
- 초 임계 상태의 물리 발포제의 소개
- 적합한 조건이 용융 상태의 폴리머로 초 임계 유체 (SCF)를 용해 (시간 / 온도 / 압력 / SCF 수준)

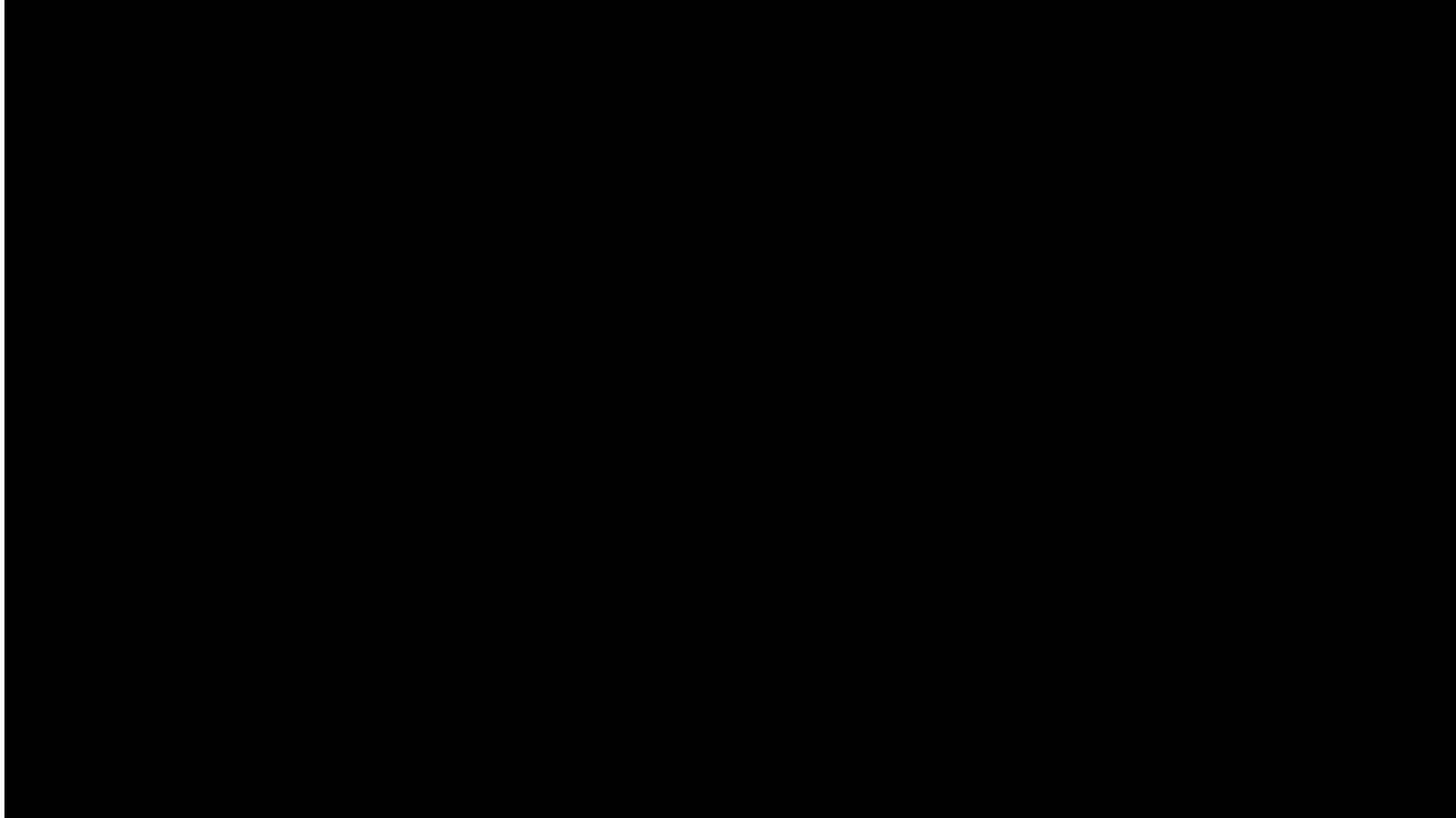


CO <sub>2</sub> : Pc = 72 bar	Tc = 31°C
N <sub>2</sub> : Pc = 34 bar	Tc = -147°C

# Super Critical Fluid (초임계 유체 ; SCF)

- 일정 온도와 압력에서 액체와 기체의 양쪽 성질을 모두 갖는 유체
  - 액체에 용해(점도 낮아짐)
  - Gas의 속성

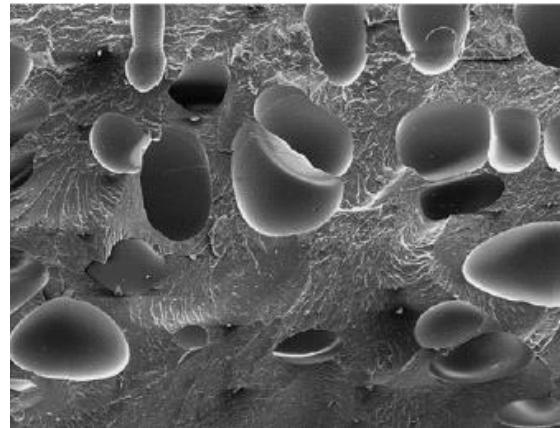




# Moldflow2016 - Bubble Nucleation Model 구현

- Bubble nucleation model 이 추가 됨 (mid-plane, dual-domain & 3D )
  - Bubble number density 계산
  - Nucleation rate 의존 결과
    - 재료 속성
    - 위치 별 온도 및 압력

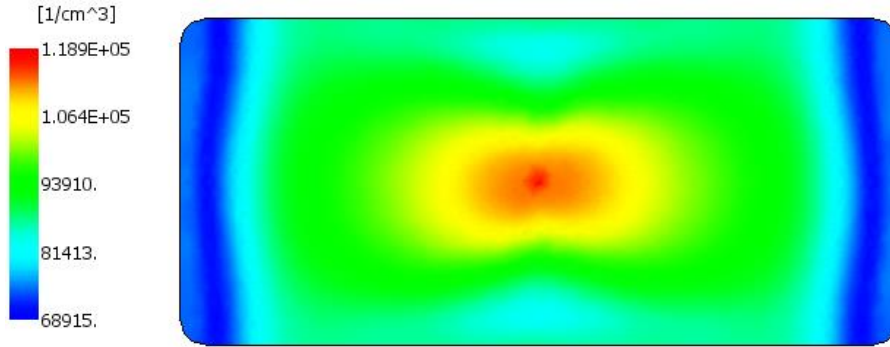
$$J = F_1 N \left[ \frac{2\sigma}{\pi m} \right]^{\frac{1}{2}} \exp \left[ \frac{-16 F_2 \pi \sigma^3}{3 k T [P_v - P_l]^2} \right]$$



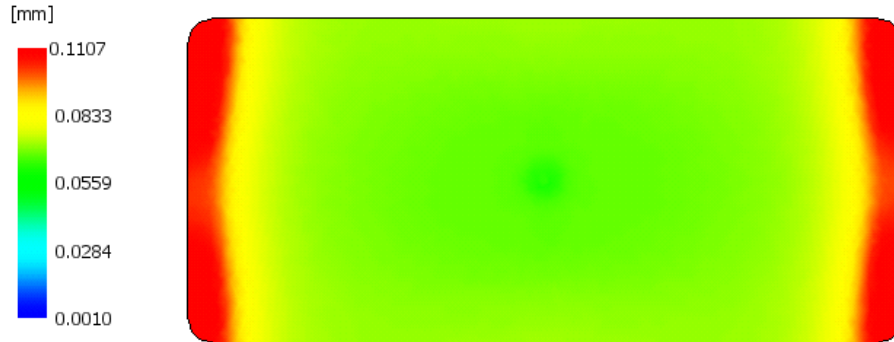
- 불균일한 nucleation 예측 가능
- 사용자가 Nucleation model 이나 Nucleation density 선택 가능

# Calculation Results for Mid-plane

- A mid-plane case for a rectangular plate



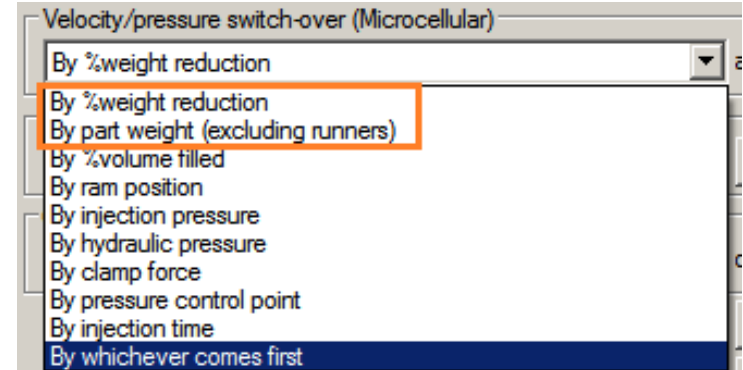
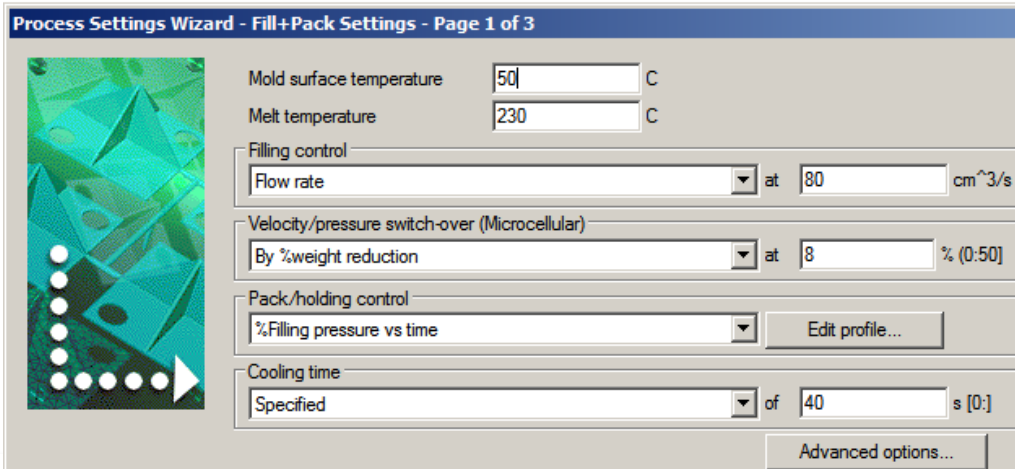
**Bubble number density**



**Bubble radius**

# Input Data Change for Microcellular Injection Molding

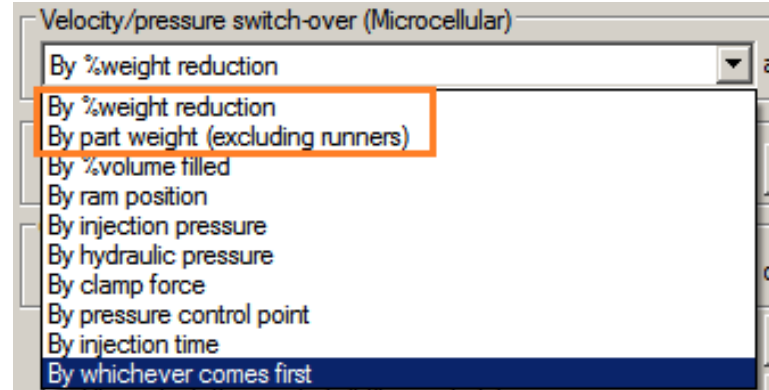
- “Initial bubble radius”: 제거함
- MuCell 공정을 위한 V/P switch-over options 추가
  - By %weight reduction
  - By part weight





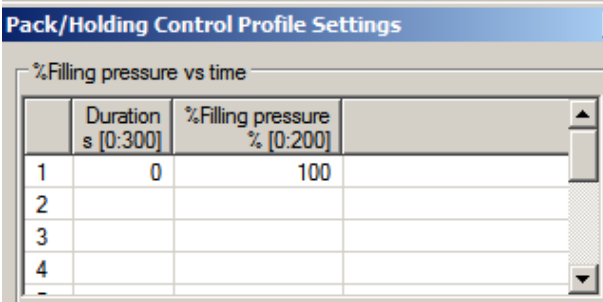
# V/P Switch-over by Weight Reduction (or Weight)

- **% Weight reduction:** 일반 사출과 비교해 **MuCell** 공정을 사용할 때 제품 중량 감소 %
- **Weight of the injection molded part:** 제품 체적과 재료 데이터(PVT, 천이온도)로부터 예측
- 직접 목표 제품 중량을 입력할 수 있음



# Packing Pressure

- **MuCell** 공정에서는 보압을 주지 않는 것이 일반적이고, 경우에 딸 낮은 보압을 적용
- **Default**로 보압 시간은 **0**
- 보압 시간을 적용하면 중량 감소가 줄게 됨



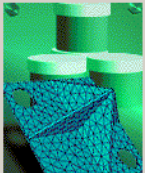
Pack/Holding Control Profile Settings

%Filling pressure vs time

	Duration s [0:300]	%Filling pressure % [0:200]	
1	0	100	
2			
3			
4			
-			

# Microcellular Process Setting

Process Settings Wizard - Microcellular Injection Molding Settings - Page 2 of 3



Microcellular foaming gas  
N2

Initial gas amount  
Initial gas concentration by weight % Initial gas concentration 0.575 % [0.1:3]

Bubble nucleation model  
Fitted Classical Nucleation Model (Parameters obtained from material data)

- **Foaming gas**
  - N2, CO2, Custom
- **Initial gas amount**
  - By weight %
  - By saturation pressure
- **Bubble nucleation model**
  - Constant nucleation density
  - **Fitted classical nucleation model**

Microcellular foaming gas

N2

N2  
CO2  
Custom

Initial gas amount

Initial gas concentration by weight %

Initial gas concentration by weight %  
Initial gas saturation pressure

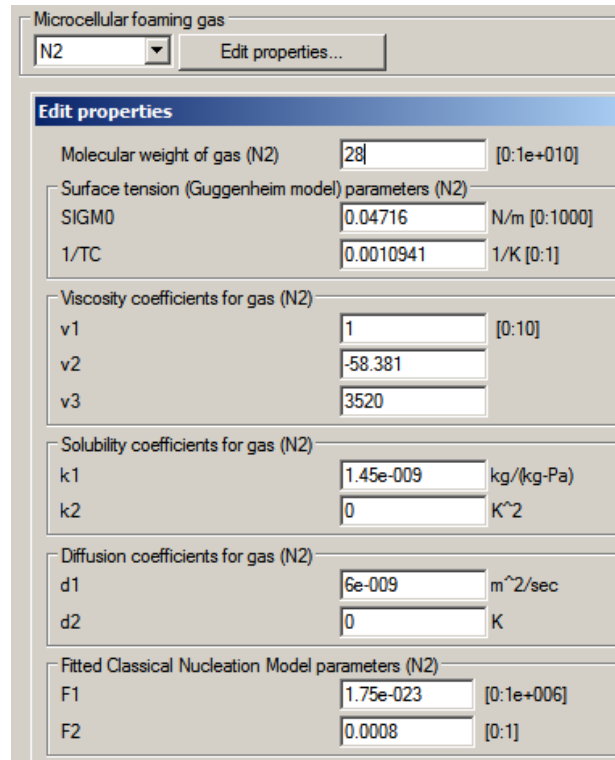
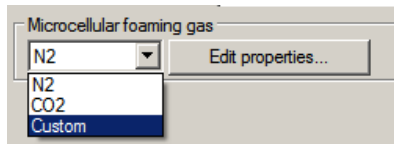
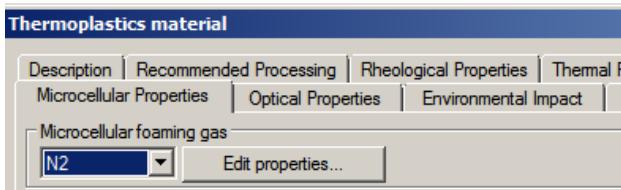
Bubble nucleation model

Fitted Classical Nucleation Model (Parameters obtained from material data)

Constant nucleation density  
Fitted Classical Nucleation Model (Parameters obtained from material data)

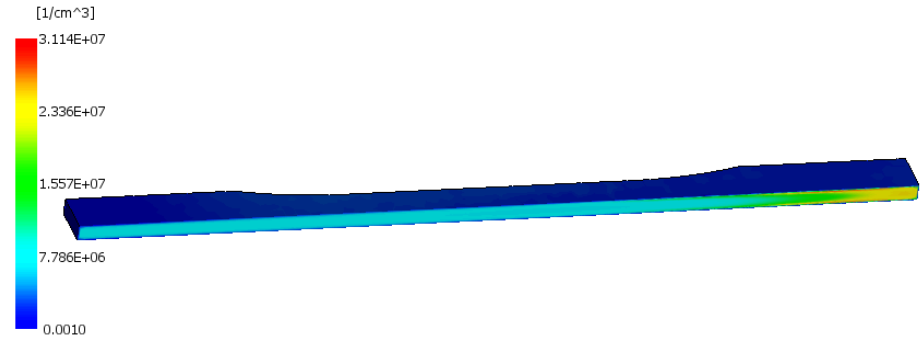
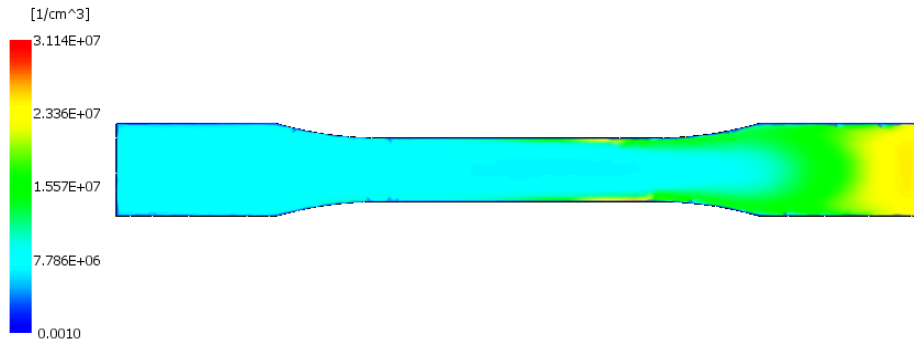
# Microcellular Material Data

- Microcellular 공정을 위한 포밍 Gas 재료 물성은 3 types
  - N2, CO2, Custom
- Data needed
  - Molecular weight (분자량)
  - Surface tension (표면 장력)
  - Viscosity coefficients for gas(점도)
  - Solubility (용해도)
  - Diffusion coefficient (확산계수)
  - Nucleation model parameters (F1,F2)



# 3D Microcellular Injection Molding Simulation

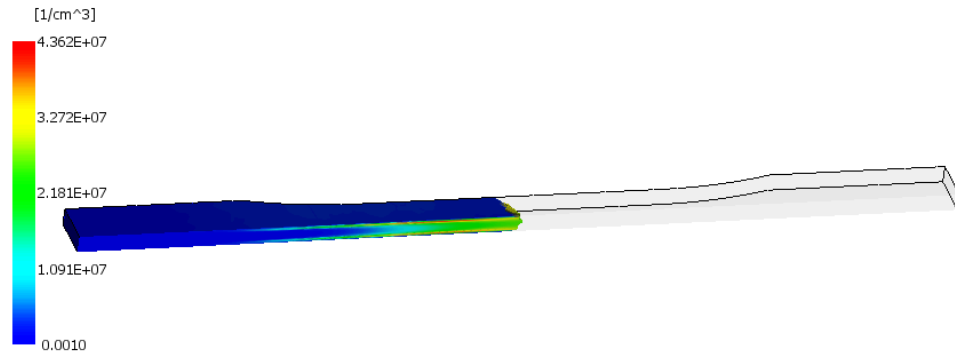
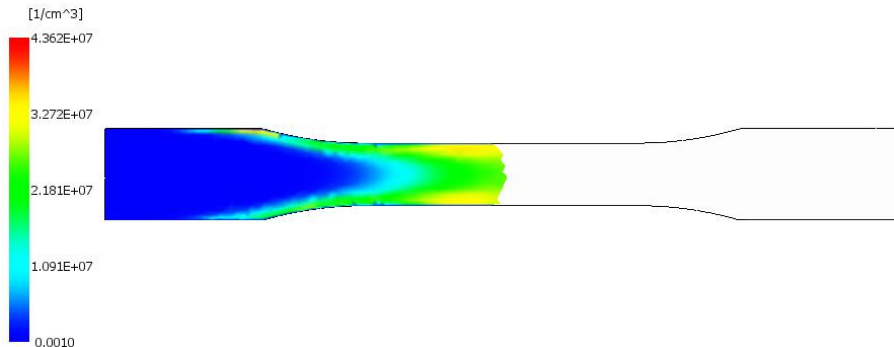
- Microcellular foaming simulation이 3D 해석 가능
  - **Bubble radius / pressure / number density calculation**
- Bubble nucleation 계산이 3D 해석 결과
- 두꺼운 parts 나 복잡한 형상에서 MuCell 해석 가능해짐



PP with N<sub>2</sub>  
0.575% gas weight

# 3D Microcellular Injection Molding Simulation

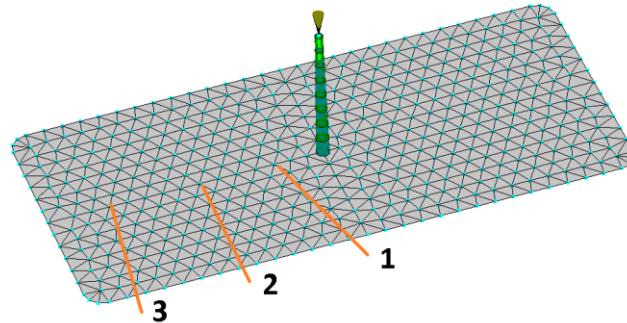
- 3D의 bubble nucleation 과 growth simulation 충전 시작 부터 계산
  - **Mid-plane/dual-domain**에서는 **V/P switch-over** 이후 부터 **packing** 까지 계산





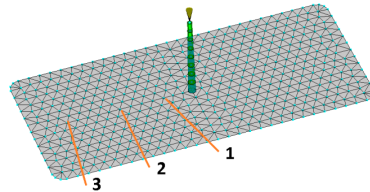
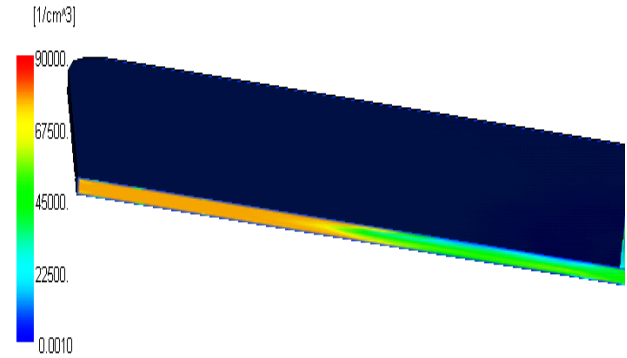
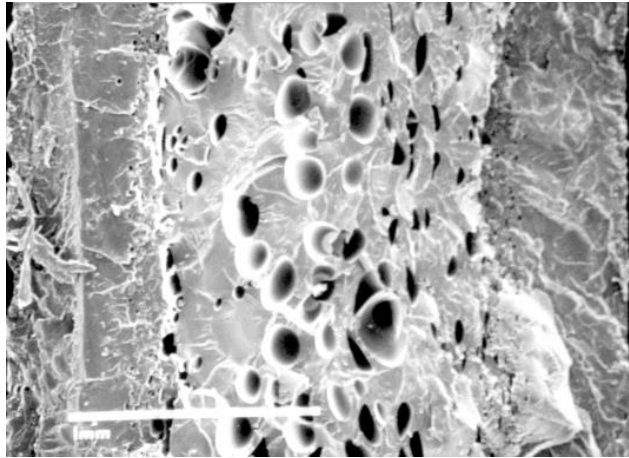
# Example 1

- 사각 판넬의 **Microcellular 사출 성형 plate**
  - **Material: Polystyrene, N2**
  - **Weight reduction: 5%**
  - **SEM(Scanning Electron Microscope, 주사 전자 현미경) pictures** 으로 3곳의 버블 개수 밀도를 예측함

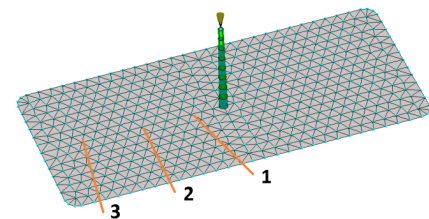
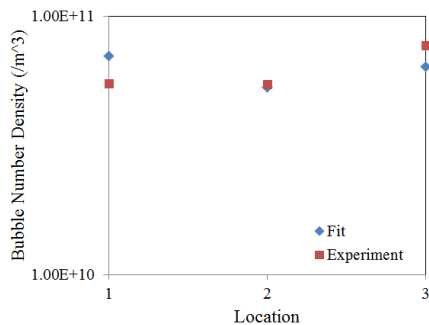


# Bubble Number Density

- 실험과 시뮬레이션을 비교
- 3D 모델의 결과

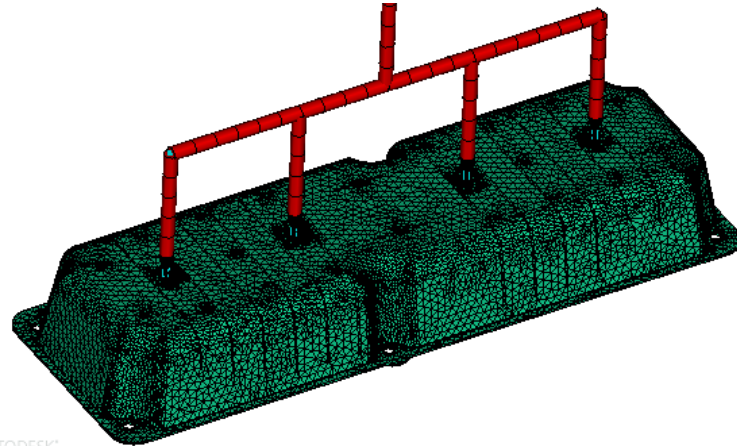


- Fitted nucleation model
  - 최적화 된 nucleation parameter로 실험과 매칭 가능
  - Nucleation은 parameter 변화에 따라 매우 민감하지 않아 비슷한 Case에 사용할 수 있음



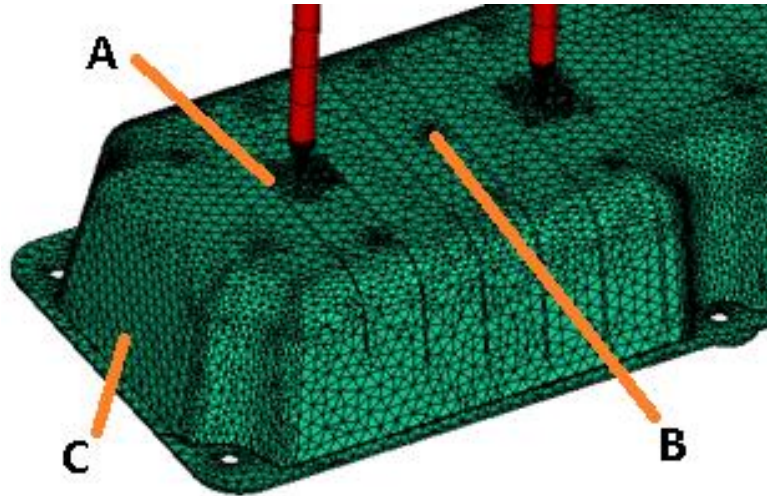
## Example 2

- 더 복잡한 제품의 **Microcellular** 사출 성형
  - **Material: Polypropylene, N2**
  - **Weight reduction: 8%**
  - **Injection speed: 2 “ / sec**
  - 주사전자현미경을 통해 각 위치에 따른 미세 발포 성형 형태 비교



# SEM Locations

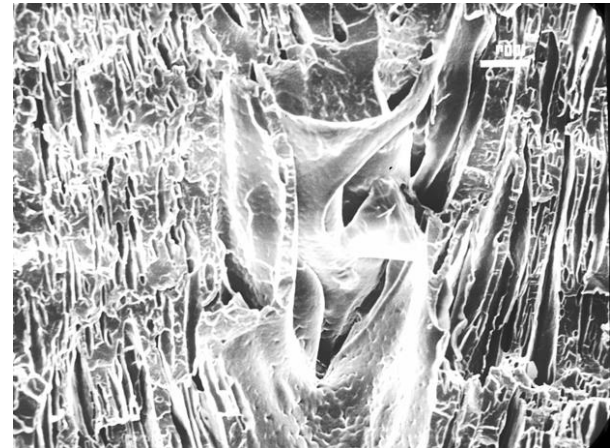
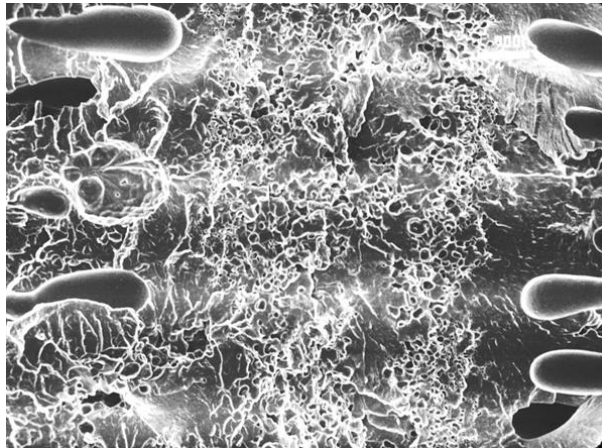
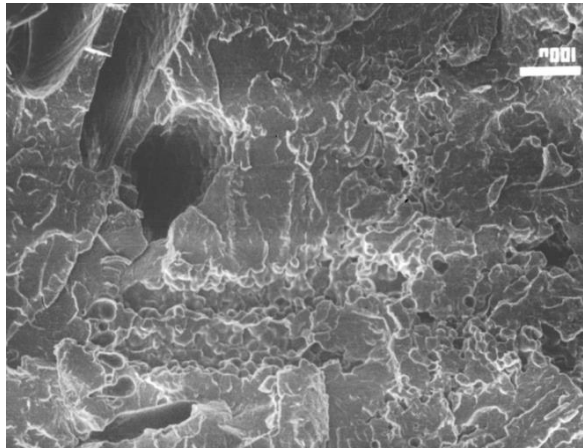
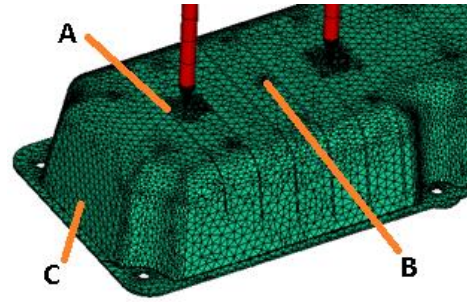
- 아래 3곳에 대하여 시뮬레이션과 SEM pictures를 비교함
- 3D model로 시뮬레이션 함



# Bubble Morphology

- A, B, C 위치에서의 SEM pictures

- A: gate 근처: 버블 개수가 작음
- B: Gate와 Gate 사이: 중심층에 작은 버블 개수가 많고, 표면 근처에 큰 버블 생성
- C: 유동 말단부: 가늘고 긴 버블 생성



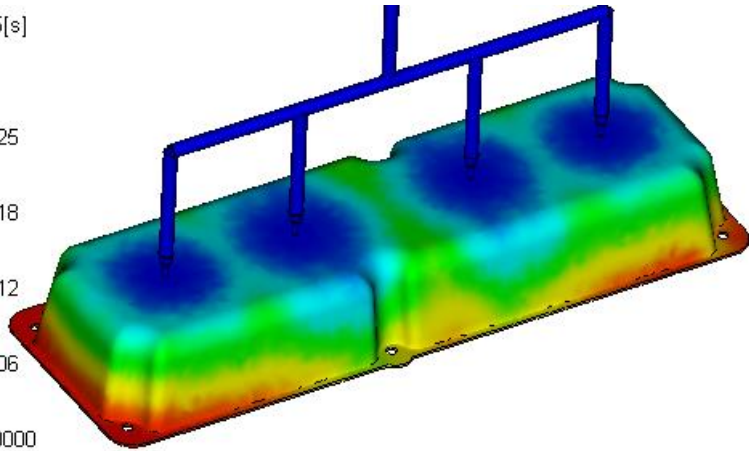


# Simulation Results

- Fill time 과 충전 시 Pressure

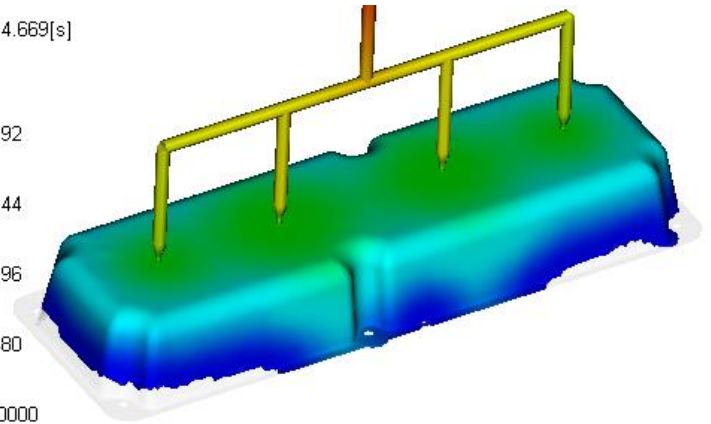
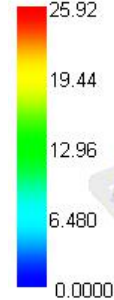
= 5.625[s]

[s]



Time = 4.669[s]

[MPa]



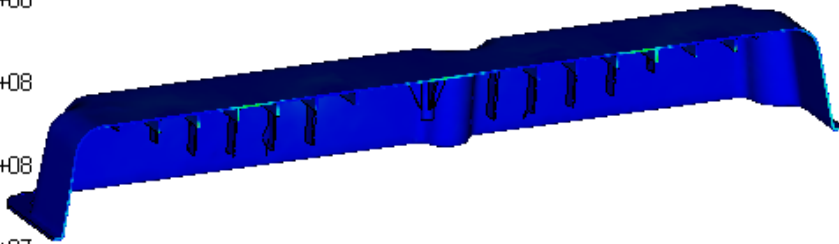


# Simulation Results

- **Bubble number density** 계산
- 관찰 결과:
  - 게이트 근처에 버블 밀도가 낮음
  - 게이트와 게이트 사이 및 유동 말단부위에 버블

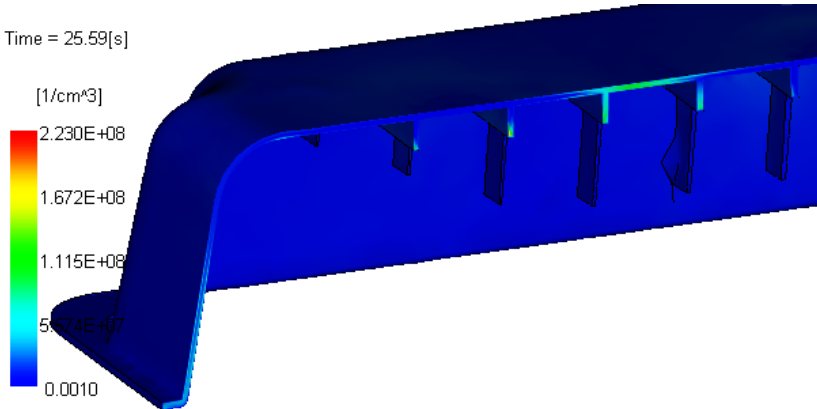
[1/cm<sup>3</sup>]

2.230E+08  
1.672E+08  
1.115E+08  
5.574E+07  
0.0010



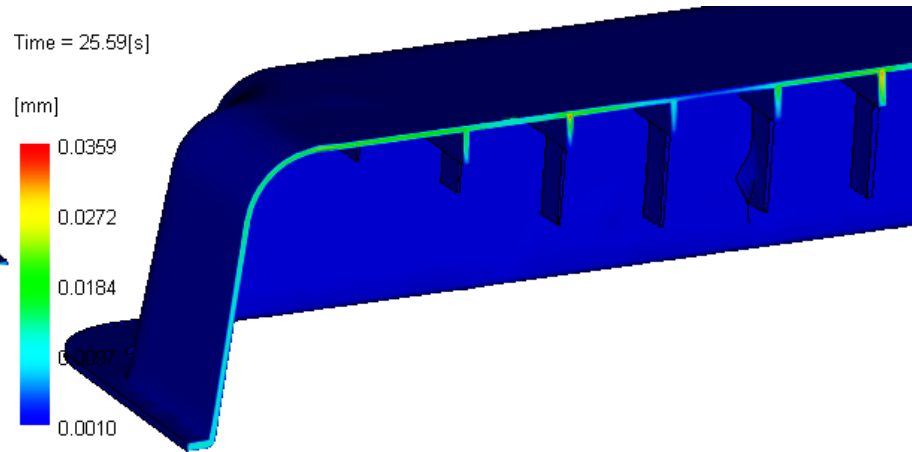
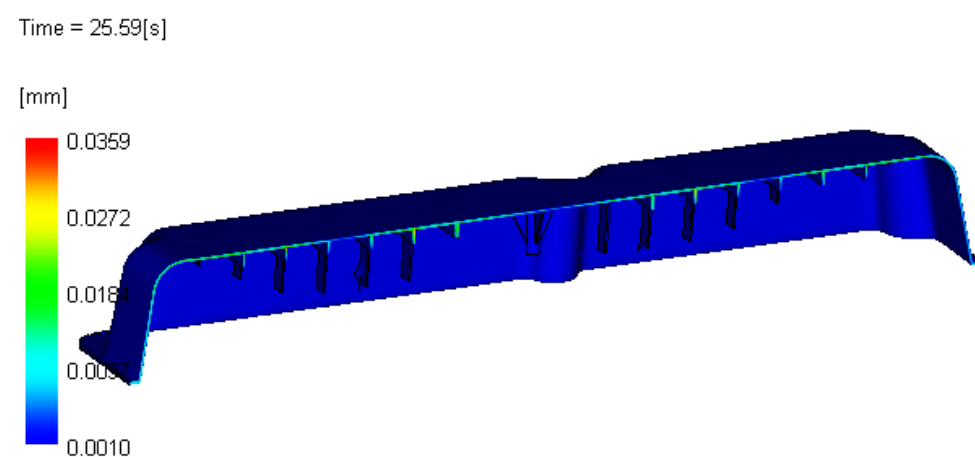
Time = 25.59[s]

[1/cm<sup>3</sup>]  
2.230E+08  
1.672E+08  
1.115E+08  
5.574E+07  
0.0010



# Simulation Results

- Bubble 반경 계산
- 관찰 결과
  - 게이트 근처와 유동 말단 부위에 큰 버블 생성
  - 게이트와 게이트 사이 작은 버블 생성

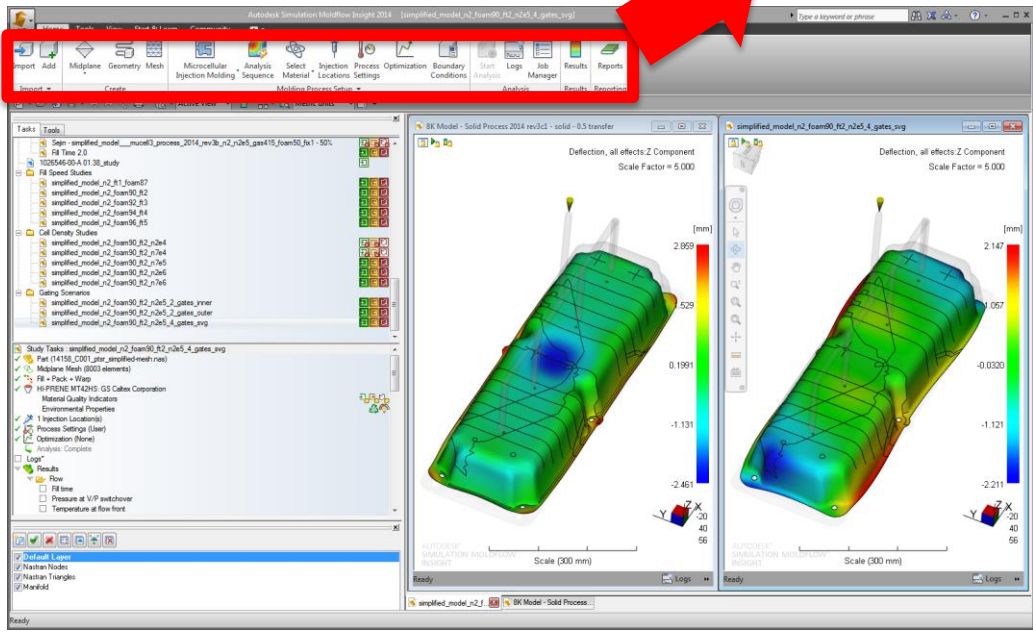
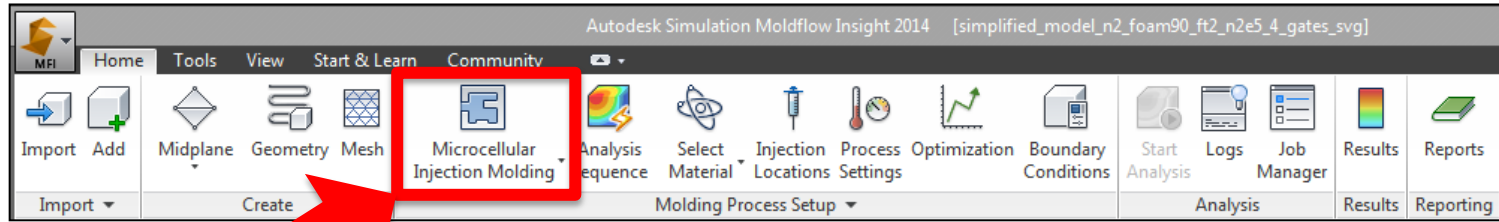


# MuCell in Moldflow 2016

# Moldflow Strategy

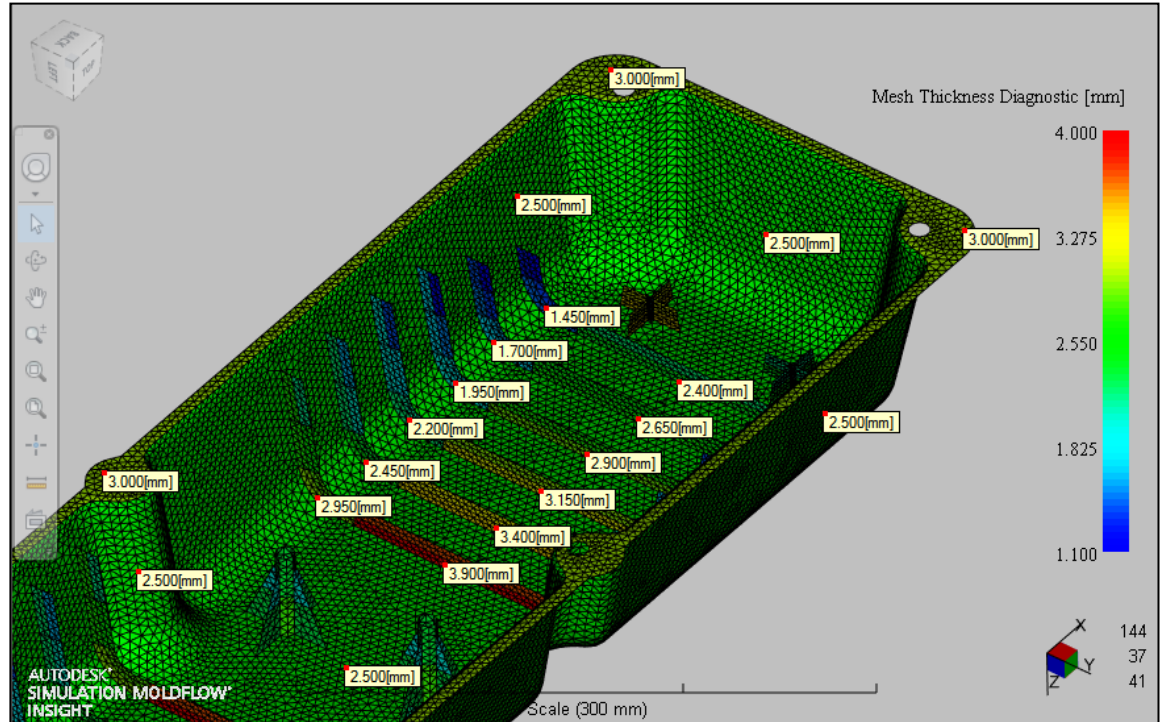
- 게이트 밸런스 위치
- 중량 감소율에 따른 해석 결과
- 사출 속도 증가에 따른 **Cell** 생성 촉진 결과
- 만약 **Full shot**이 불가능할 때 중량 감소율을 약간 줄임

# Step 1 - Microcellular Injection Molding Module



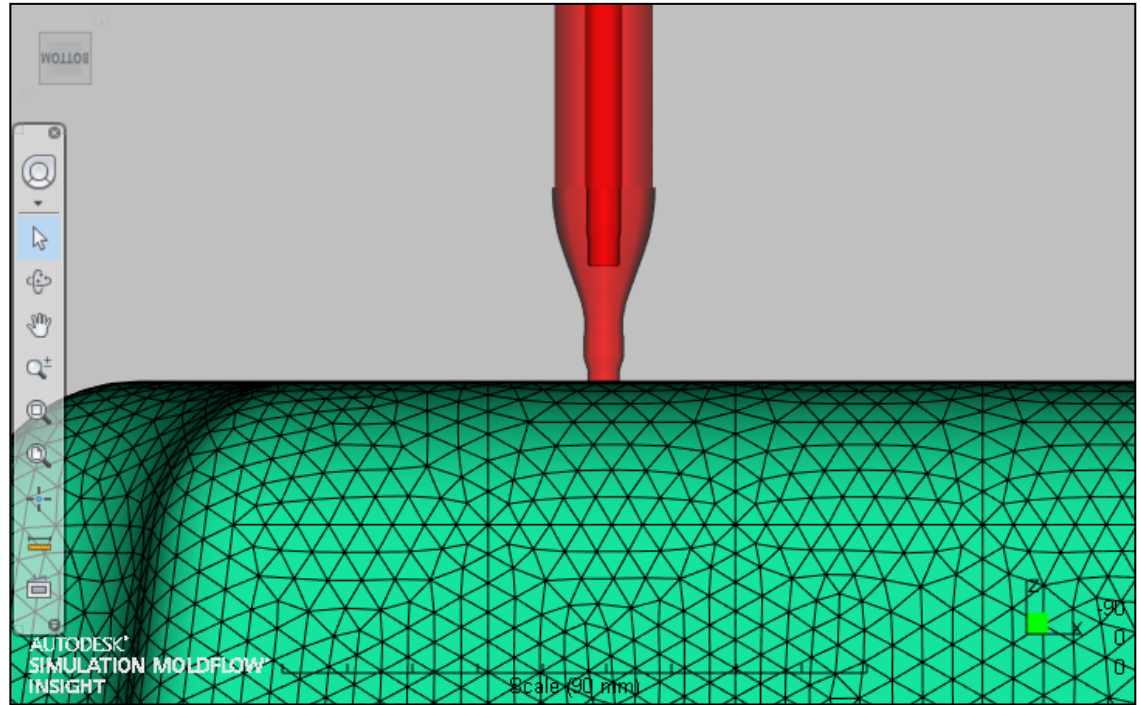
# Step 2 – Part Modeling

- Midplane
- Dual Domain
- **3D Added!**
- 기타 특별히 고려해야 할 사항 없음



# Step 3 – Mold Modeling

- Hot Runners Valve Gates! 필요
- 기타 특별히 고려해야 할 사항 없음





# Step 4 – Process Modeling – The Old Way

Process Settings Wizard - Microcellular Injection Molding Settings - Page 2 of 3

Volume filled at start of foaming	89	% [0:100]
Initial bubble radius	0.001	mm [0:1]
Number of cells per volume	2e+005	1/cm <sup>3</sup> [0:1e+014]
Initial gas concentration	0.4	% [0:10]

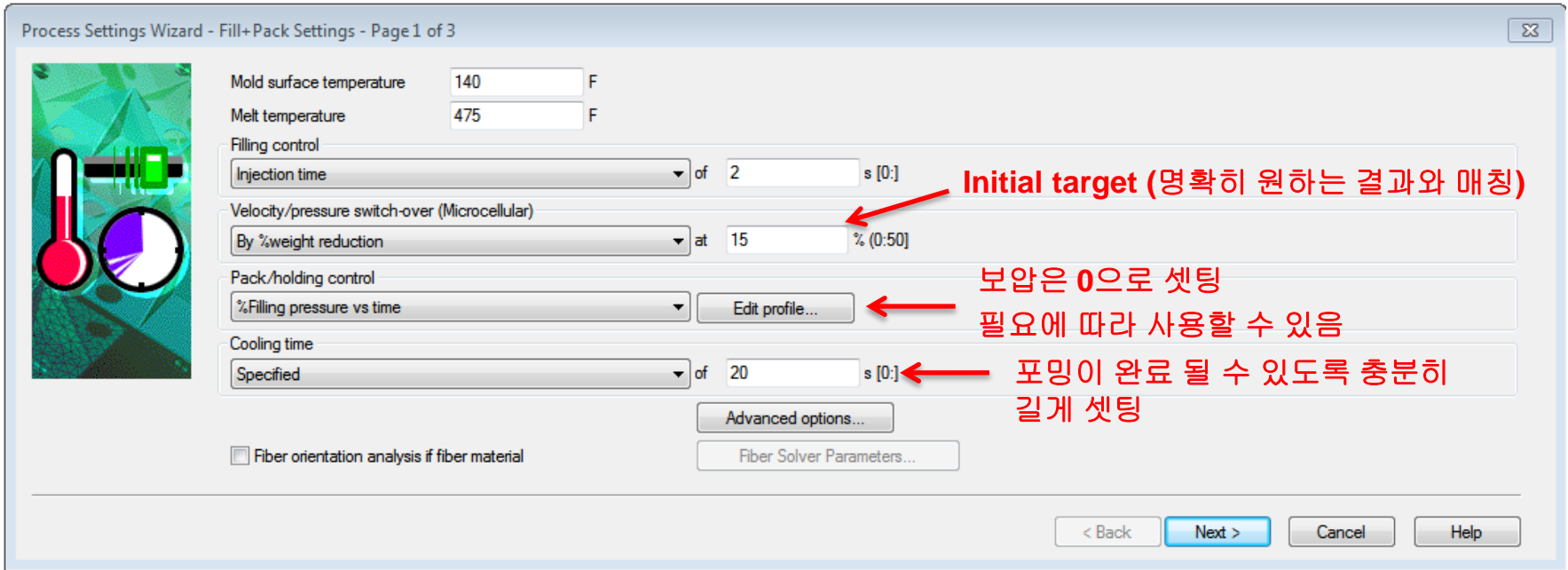
**현재까지는?**

- 핵 생성 모델이 없었음
- 수정된 점도 고려
- 버블 성장을 위한 시작점

< Back   Next >   Cancel   Help

# Step 5 – Process Modeling – The New Way

Process Settings Wizard - Fill+Pack Settings - Page 1 of 3



The image shows a software interface for setting injection molding parameters. It includes fields for mold and melt temperatures, filling control options like injection time and velocity/pressure switch-over, and pack/holding control options. Red arrows point to specific values with Korean text explaining their significance: 'Initial target' for injection time, '보압은 0으로 셋팅' (Set backpressure to 0) for the velocity/pressure switch-over, and '포밍이 완료 될 수 있도록 충분히 길게 셋팅' (Set long enough so that foaming can be completed) for the cooling time.

Mold surface temperature: 140 F  
Melt temperature: 475 F

Filling control  
Injection time: 2 s [0:] **Initial target (명확히 원하는 결과와 매칭)**

Velocity/pressure switch-over (Microcellular)  
By %weight reduction: 15 % (0.50) **보압은 0으로 셋팅**

Pack/holding control  
%Filling pressure vs time: Edit profile... **필요에 따라 사용할 수 있음**

Cooling time  
Specified: 20 s [0:] **포밍이 완료 될 수 있도록 충분히 길게 셋팅**

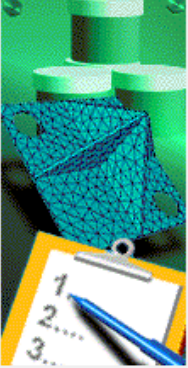
Advanced options...  
Fiber Solver Parameters...

Fiber orientation analysis if fiber material

< Back Next > Cancel Help

# Step 5 – Process Modeling


Process Settings Wizard - Microcellular Injection Molding Settings - Page 2 of 3



Microcellular foaming gas  
N2

Initial gas amount  
Initial gas concentration by weight % Initial gas concentration 0.415 % [0.1:3]

Bubble nucleation model  
Fitted Classical Nucleation Model (Parameters obtained from material data)



## Give it Some Gas!

< Back  Cancel Help

# Step 6 – Analyze (Midplane)

Filling phase: Status: U = Velocity control  
P = Pressure control  
F = Foaming  
U/P= Velocity/pressure switch-over

Time (s)	Volume (%)	Pressure (MPa)	Clamp force (tonne)	Flow rate (cm <sup>3</sup> /s)	Status
0.001	0.04	"Valve gate controller defaults" # 1 (Elem# 70231)			opened.
0.001	0.04	"Valve gate controller defaults" # 1 (Elem# 70268)			opened.
0.001	0.04	"Valve gate controller defaults" # 1 (Elem# 70305)			opened.
0.001	0.04	"Valve gate controller defaults" # 1 (Elem# 70342)			opened.
0.102	1.49	17.39	0.31	394.40	U
0.201	5.93	19.90	1.33	473.59	U
0.300	10.71	20.72	3.09	478.56	U
0.406	15.80	21.39	5.65	479.82	U
0.506	20.66	21.90	8.41	481.39	U
0.605	25.46	22.33	11.26	483.04	U
0.701	30.08	22.73	14.53	483.46	U
0.807	35.20	23.27	20.25	482.17	U
0.904	39.84	23.82	26.00	483.17	U
1.011	44.90	24.47	34.35	482.71	U
1.107	49.46	25.05	42.20	482.77	U
1.204	54.11	25.59	49.87	483.41	U
1.311	59.17	26.24	59.35	483.67	U
1.404	63.56	26.84	68.32	484.36	U
1.510	68.52	27.64	81.64	483.72	U
1.611	73.27	28.46	94.42	484.78	U
1.700	77.43	29.12	104.82	485.52	U
1.802	82.19	29.94	118.47	485.79	U
1.900	86.76	30.75	132.00	486.10	U
1.953	89.19	31.28	141.40	446.00	U/P(M)
1.954	89.21	1.46	35.84	201.14	F
2.001	93.57	1.70	23.98	673.67	F
2.101	97.36	1.92	28.22	233.35	F
2.201	98.79	2.01	29.98	88.52	F
2.300	99.54	2.06	30.90	65.24	F
2.374	99.92	2.08	31.36	39.14	F
2.375	100.00	2.08	31.24	31.93	Filled

Packing phase:

Time (s)	Packing (%)	Pressure (MPa)	Clamp force (tonne)	Status
2.375	2.11	1.90	31.57	F
3.916	9.81	2.09	36.44	F
5.876	19.61	2.09	35.29	F
7.832	29.39	2.12	33.37	F
9.789	39.18	2.14	27.94	F
11.747	48.97	2.15	25.93	F
13.706	58.76	2.17	19.04	F
15.667	68.57	2.20	13.52	F
17.622	78.34	2.23	6.60	F
19.582	88.15	2.27	2.63	F
21.541	97.94	2.27	0.95	F
21.957	100.00	2.27	0.94	F

Filling phase results summary :

Maximum injection pressure (at 1.9532 s) = 31.2782 MPa

End of filling phase results summary :

Time at the end of filling = 2.3753 s  
 Total weight (part + runners) = 791.4841 g  
 Maximum Clamp force - during filling = 132.0934 tonne

# Step 6 – Analyze (3D)

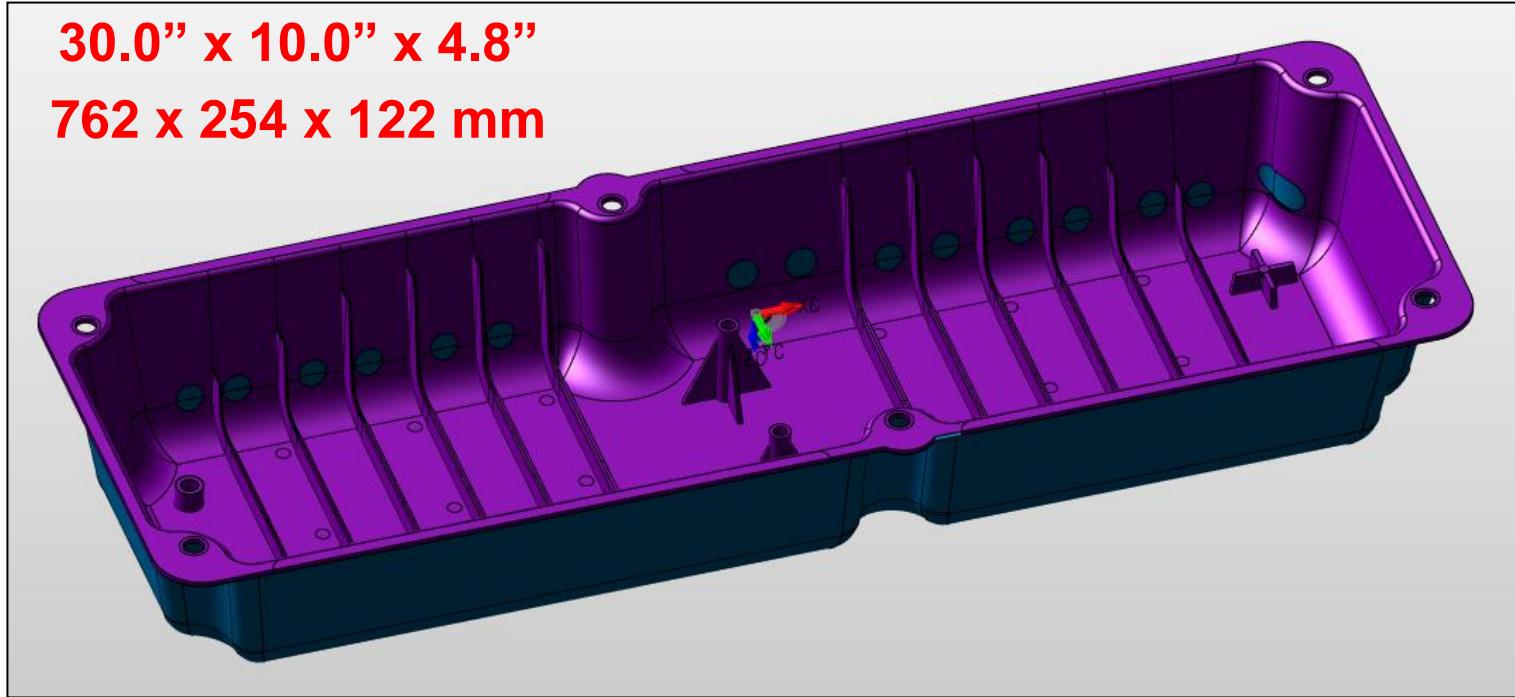
1.422	69.300	3.259e+01	7.42e+01	479.655	6.48	U
1.478	71.108	3.301e+01	8.11e+01	479.671	6.65	U
1.503	72.695	3.319e+01	8.44e+01	479.661	6.69	U
1.540	74.549	3.345e+01	8.89e+01	479.513	6.77	U
1.574	76.354	3.370e+01	9.30e+01	479.630	6.85	U
1.629	78.080	3.408e+01	9.87e+01	480.127	7.02	U
1.647	79.219	3.421e+01	1.01e+02	480.357	7.04	U
1.669	80.358	3.437e+01	1.04e+02	480.092	7.09	U
1.702	82.007	3.461e+01	1.08e+02	480.069	7.15	U
1.734	83.610	3.485e+01	1.12e+02	480.156	7.21	U
1.765	85.412	3.511e+01	1.17e+02	480.113	7.26	U
1.818	87.023	3.553e+01	1.23e+02	480.446	7.41	U
1.843	88.604	3.577e+01	1.28e+02	480.414	7.43	U
1.898	90.208	3.634e+01	1.38e+02	480.206	7.58	U

Velocity/pressure	switch-over	by %weight	reduction =	20.0000 %	
1.910	91.180	3.650e+01	1.42e+02	479.376	7.58 U/P
1.933	91.320	1.763e+01	1.10e+02	0.000	7.80 F
1.945	91.914	1.509e+01	9.01e+01	0.000	7.92 F
1.963	92.211	1.146e+01	7.16e+01	0.000	8.11 F
1.992	92.650	8.254e+00	5.39e+01	0.000	8.40 F
2.028	93.322	5.843e+00	4.11e+01	0.000	8.74 F
2.073	93.645	4.149e+00	3.35e+01	0.000	9.18 F
2.127	93.951	2.990e+00	3.04e+01	0.000	9.69 F
2.198	94.456	2.242e+00	3.00e+01	0.000	10.30 F
2.298	94.955	1.819e+00	3.04e+01	0.000	11.12 F
2.398	95.594	1.674e+00	3.07e+01	0.000	11.87 F
2.498	96.193	1.818e+00	3.11e+01	0.000	12.60 F
2.598	96.718	1.912e+00	3.17e+01	0.000	13.30 F
2.698	97.320	1.960e+00	3.20e+01	0.000	13.99 F
2.798	97.800	1.992e+00	3.22e+01	0.000	14.67 F
2.883	98.543	2.012e+00	3.25e+01	0.000	15.18 F
2.983	98.576	2.051e+00	3.27e+01	0.000	15.91 F
3.083	99.009	2.073e+00	3.24e+01	0.000	16.55 F
3.183	99.668	2.103e+00	3.24e+01	0.000	17.12 F
3.283	99.999	2.138e+00	3.35e+01	0.000	17.74 F
3.383	100.000	2.156e+00	3.32e+01	0.000	18.44 Filled

# Case Example – Correlation

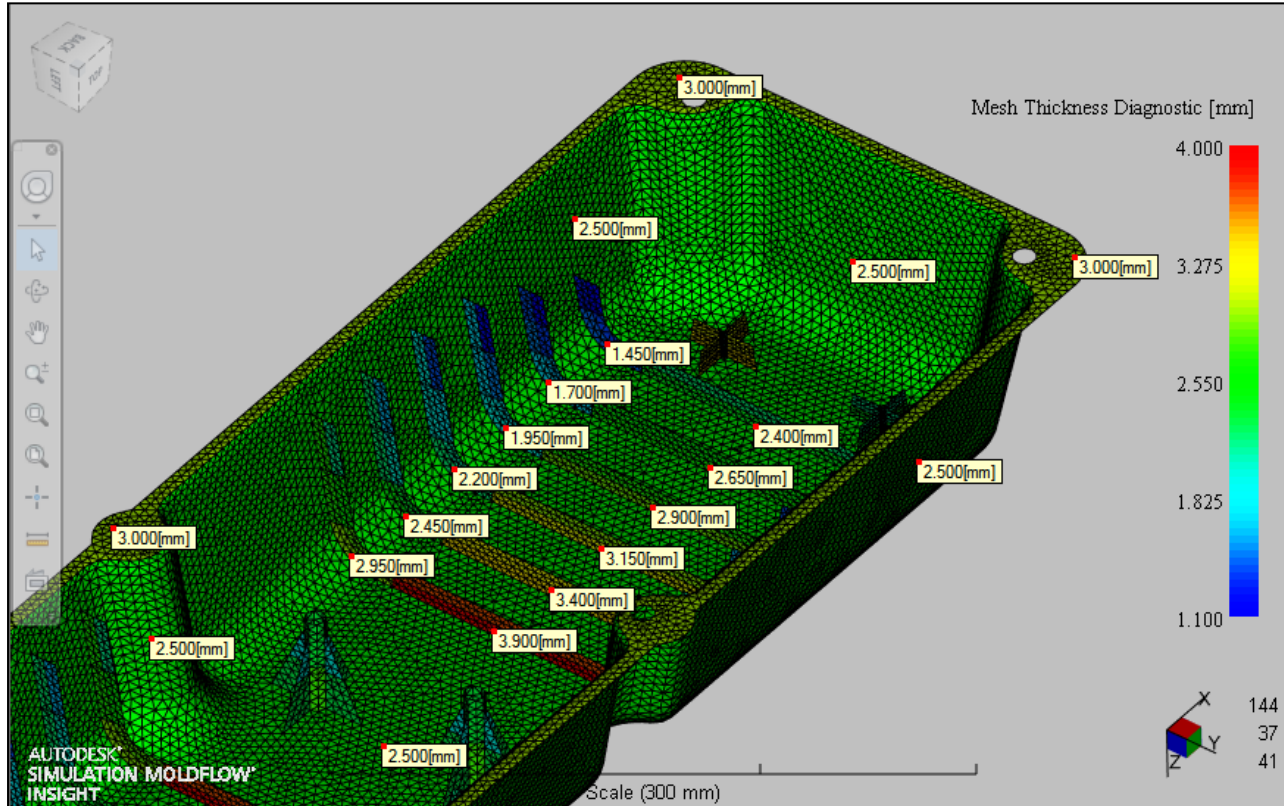
# The Part – Oil Pan

30.0" x 10.0" x 4.8"  
762 x 254 x 122 mm





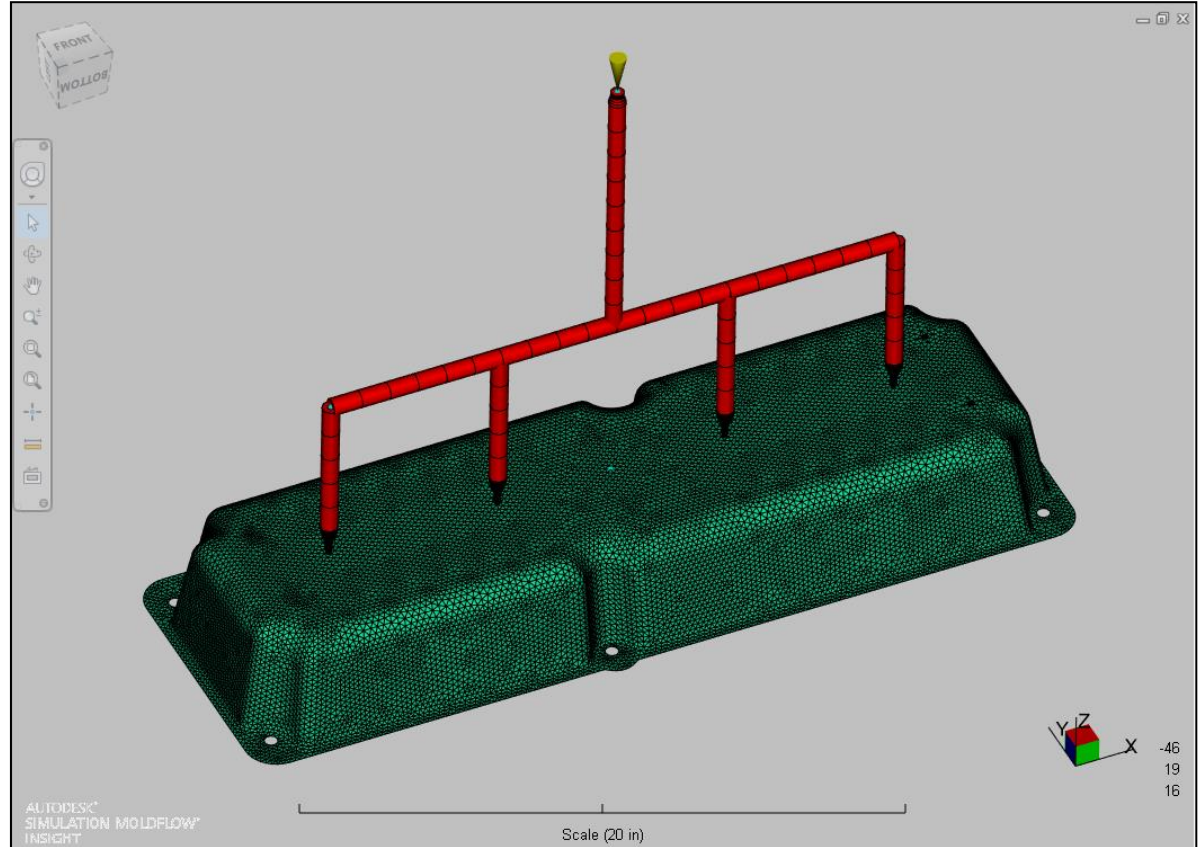
# The Part – Moldflow Model



# The Mold – Manifold Design

## Hot Manifold:

- Synventive 16E
- Inlet – 16.0 mm
- Main Bore – 16.0 mm
- Nozzle Bore – 16.0 mm
- Valve Pins – 6.0 mm
- Gate Orifices – 5.0 mm



# Molded Parts – Achieved 11% weight reduction



# Molded Parts

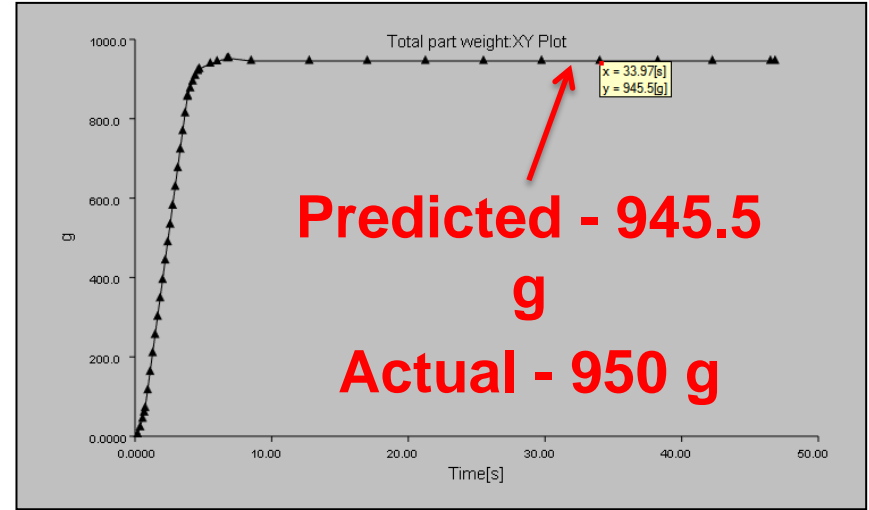
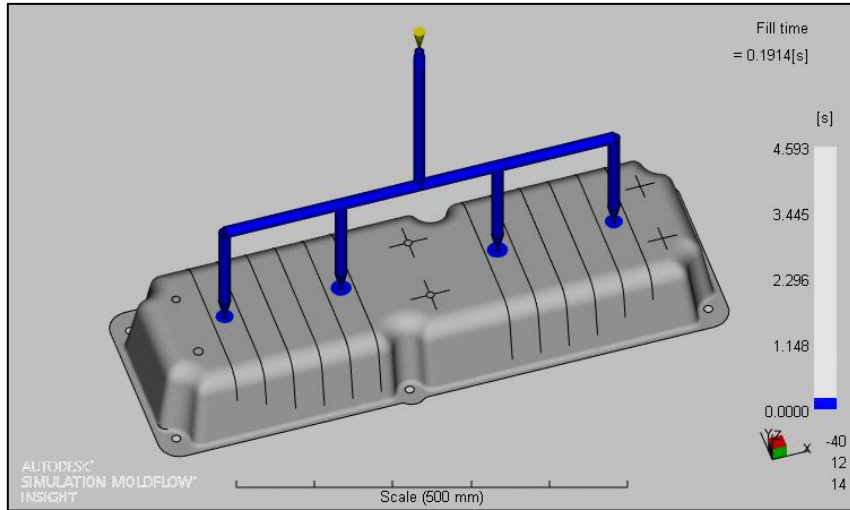
Full Shot

Short Shot



# Solid Shot – Part Weight Results

## Total Part Weight



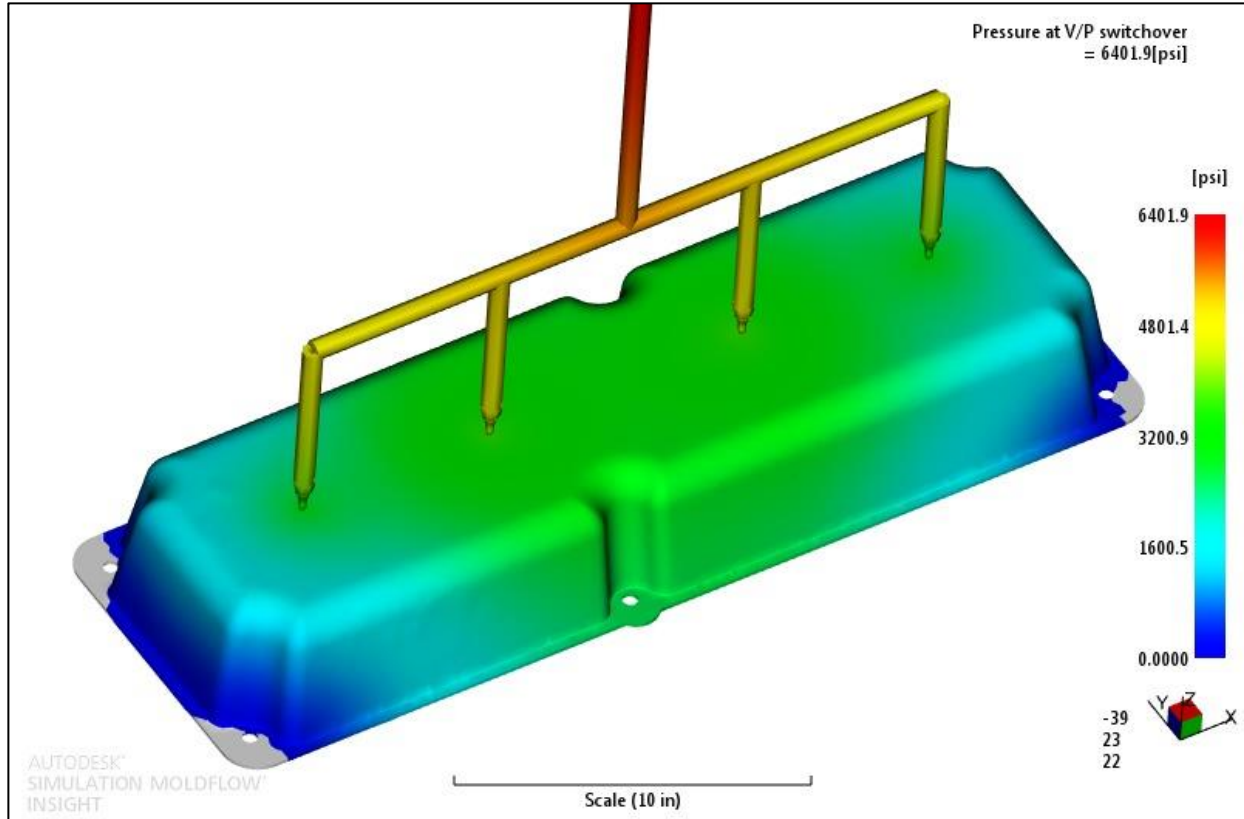
# MuCell Shot – Weight Results

Fill Time (sec.)	V/P Switchover (By % Weight Reduction)	Predicted Part Weight (g)	Predicted Weight Reduction
2.0	11%	868.9	12.2%
2.0	15%	837.4	15.4%
2.0	20%	791.5	20.1%
2.0	25%	746.4	24.6%
2.0	30%	Short shot	

Calculated Reference Solid Part  
Weight = 990g

# Pressure Prediction

Predicted – 6401 psi

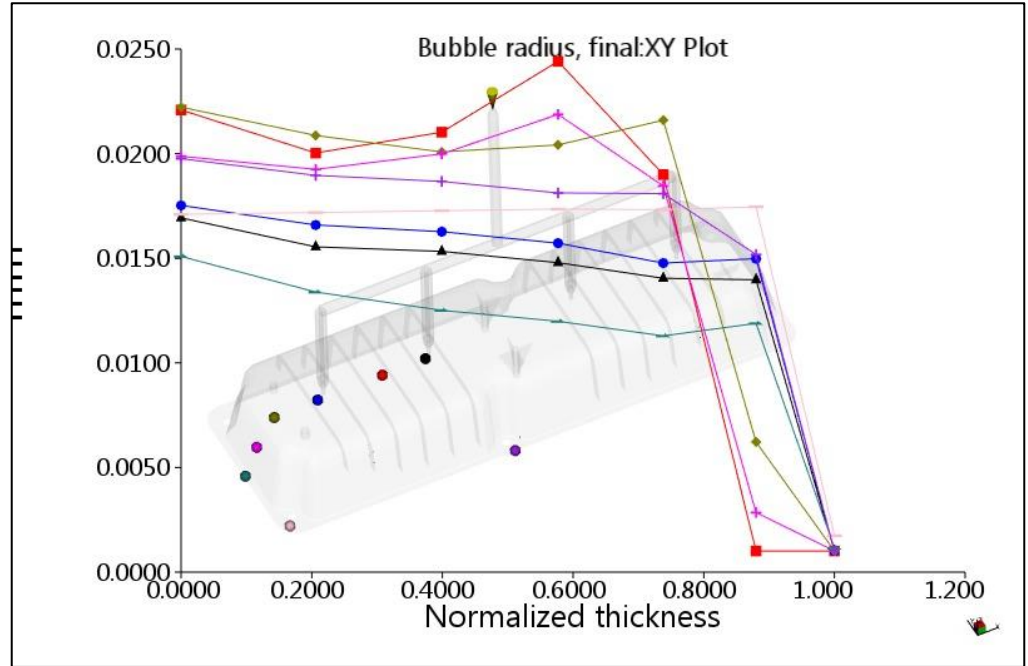




# Bubble Radius Results

## Trends

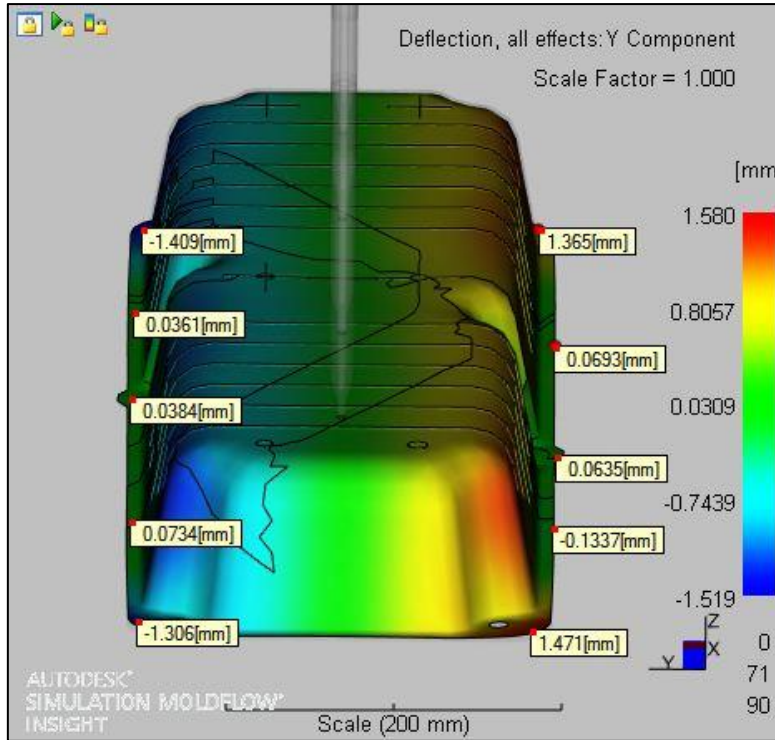
- Higher pressure = small radius
- Higher temp = large radius



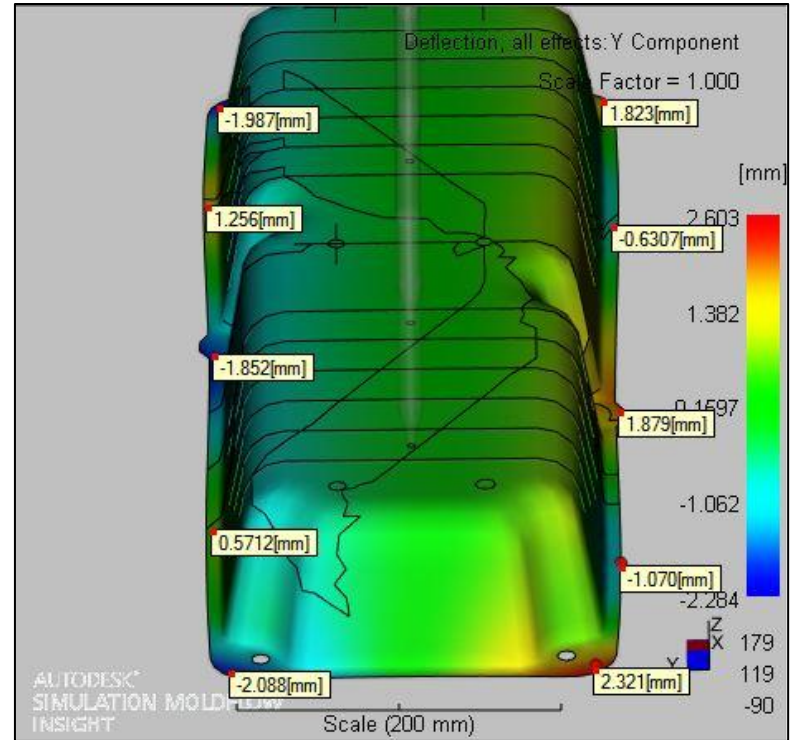
# Warpage – Molded Samples



# Predicted Warpage – (ASMI 2015)

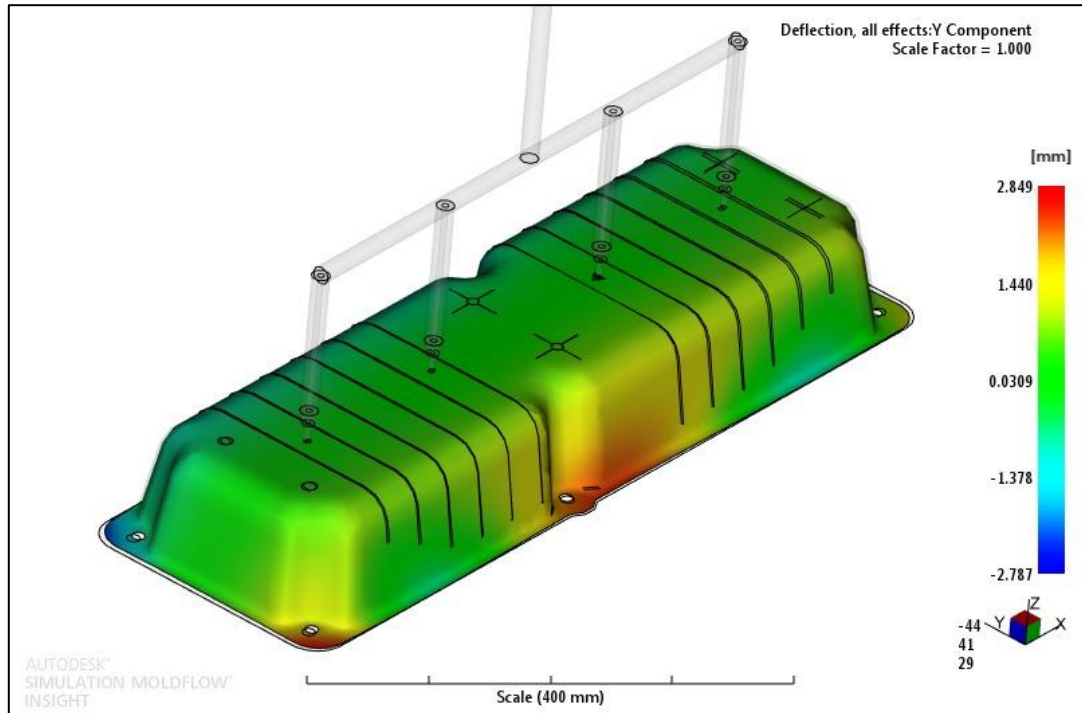


**Solid**



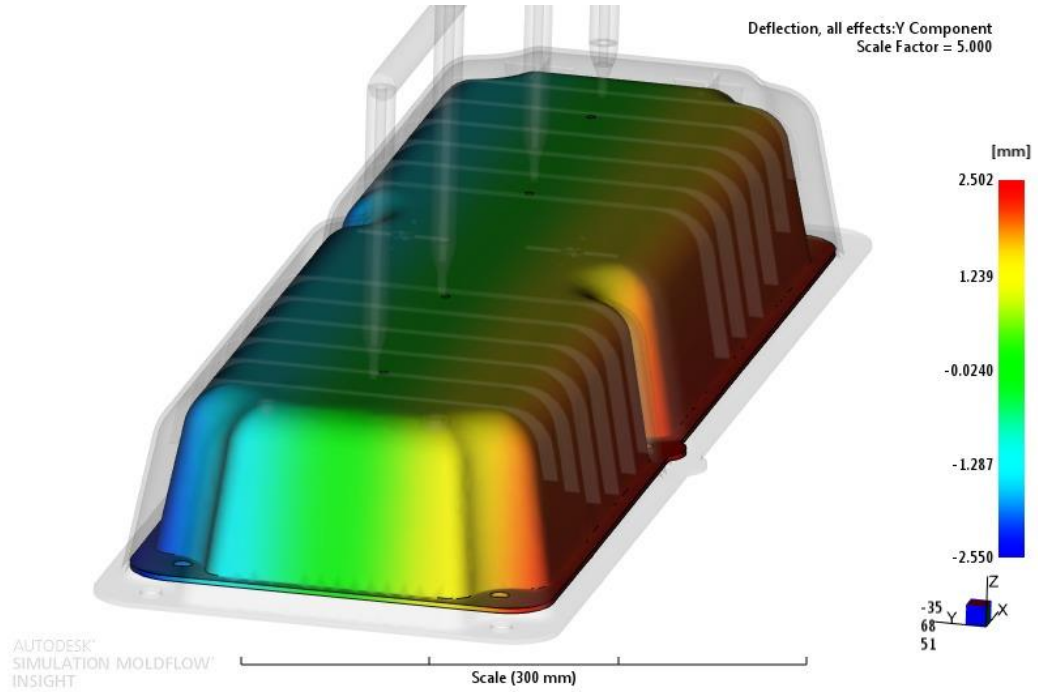
**MuCell**

# Predicted Warpage – 2016 (no CRIMS)



**MuCell**

# Predicted Warpage – 2016 (3D)



**MuCell**

# Conclusion

- 현재 bubble nucleation model 로 MuCell 사출 성형에 대하여 품질 예측이 가능하다.
- Nucleation parameters 는 경우에 따라 조정이 필요할 수 있다.
- 3D Microcellular 시뮬레이션은 경우에 따라 Mid Plane 시뮬레이션 보다 더 사실적인 시뮬레이션 결과를 제공한다.

8:2

