Orientation

강의명: 금속유동해석특론 (AMB2039)

정영웅

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HOMEPAGE: HTTP://YOUNGUNG.GITHUB.IO

Outline

- 강의 소개
- 평가
- 강의 진행 방식 및 규칙

강의 소개

- 창원대 신소재공학부 대학원
- 시간
  - 월 (85603) 9:00am – 12:00pm
- 15주

평가

- 등급 평가 (ABCDF)
- 평가 요소
  - 프로젝트 발표
    - 학생 개개인의 연구 과제(혹은 문헌조사 결과)에 대한 발표 (영문 발표 질의 형식)
  - 구술 면담 평가
    - 강의 주제 내용에 대한 이해를 구술 면담의 형태로 최종 평가
- 출결
  - 수업시작 10분까지 출석 인정
  - 10분-30분까지 지각
  - 30분- 결석
  - 주의: 총 수업의 ¼ 이상 결석시 자동으로 F 학점 (needed to check for graduates?)
- 수업 중 질문에 대한 응답은 평가 항목이 아닙니다.

강의 진행 방식 및 규칙

- 강의 슬라이드를 수업 교재로 간주
- 그외 참고 문헌:
  - Metal Forming, W. F. Hosford and R. M. Caddel (번역판: 금속소성가공 허무영)
  - The Mathematical Theory of Plasticity, Rodney Hill
  - Texture and Anisotropy, Kocks, Tomé, Wenk
  - Fundamentals of mtal forming, Robert H. Wagoner, Jean-Loup Chenot
- 강의 중 질의 응답.
  - **There's no such thing as stupid question in my class.**
  - Just because one person may know less than others, they should not be afraid to ask rather than pretend they already know.
  - 질문에 대한 응답과 관련하여서는 어떠한 penalty도 없습니다.
  - 아무 말 대잔치 환영
- 상시 feedback (전, 중, 후) - #52-208
- 강의 노트
  - 되도록 수업 전주 금요일에 업로드 (수업커뮤니티 혹은 홈페이지를 통해)
- 수업후 과제
  - (계획) 되도록 수업후 과제없이 진행

Chapter1

Introduction

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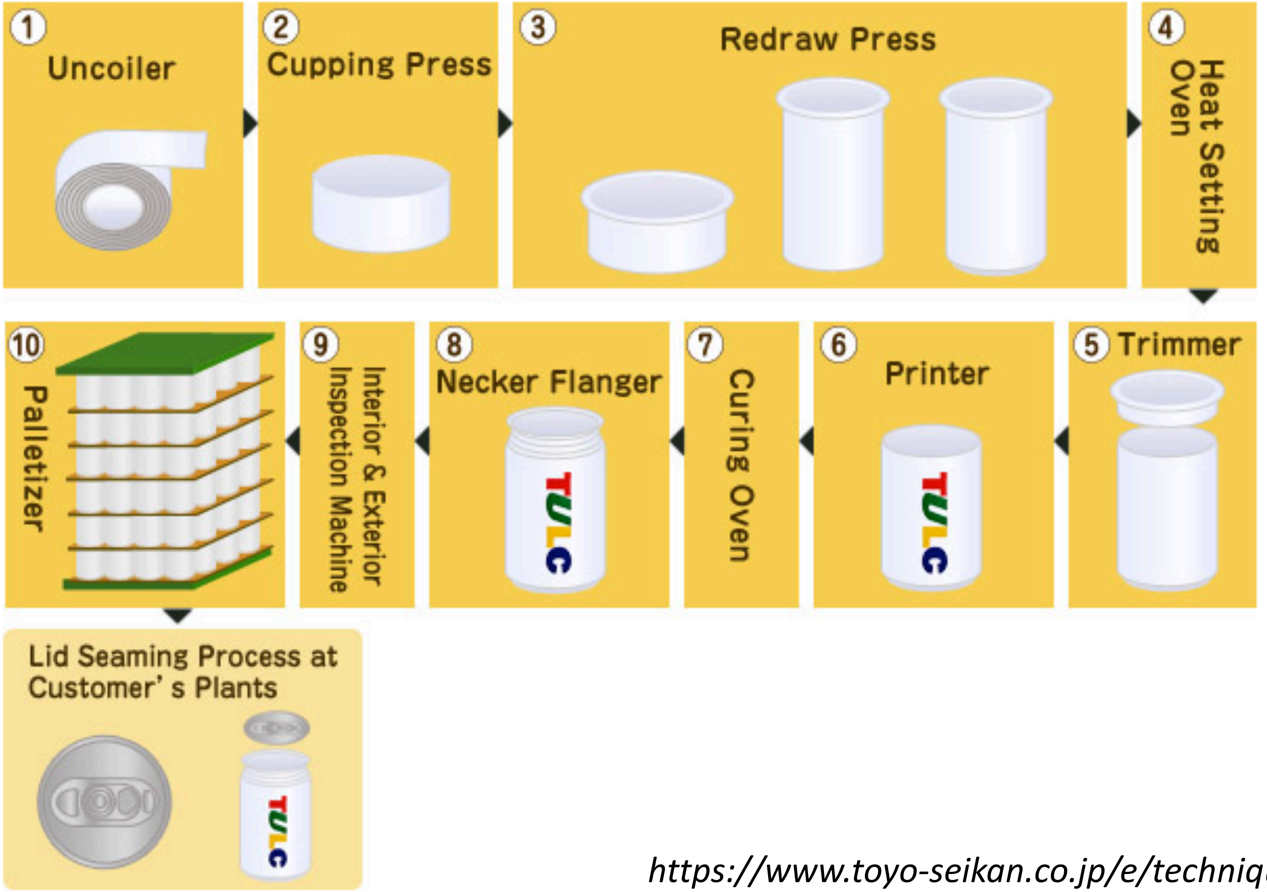
Objectives

- Understand pros and cons of a few forming processes
  - Powder forming
  - Injection molding
  - Additive manufacturing
- Understand metal forming (소성 가공)
- What is constitutive model
- Mechanical properties and the associated physical quantities
  - Stress
  - Strain

Shaping & Forming

- Components in desired shape.
- How to have a product in desired shape made of a certain kind of material?



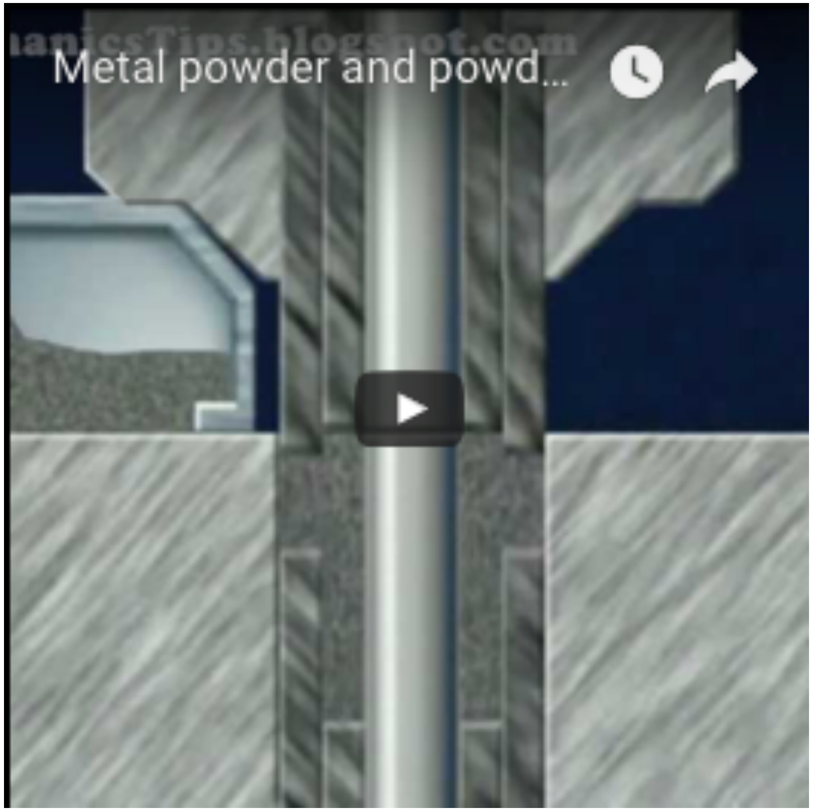
https://www.toyo-seikan.co.jp/e/technique/can/making/

소성가공이란?

- 재료의 가공법의 종류; 물질의 소성을 활용한 가공; 본 강의는 금속에 한정
- 재료 가공법에는
  - 부가 가공 (additive manufacturing) – 3D printer
  - 제거 가공 (절삭, 절단)
  - 성형 가공 (소성 가공, 분말 성형, 사출 성형 등)

- Q. 분말 성형 (powder forming)?
- Q. 사출 성형 (injecting molding)?
- Q. 3D print?
- Q. 다양한 가공법이 존재하는 이유는?

분말 성형 (powder forming)



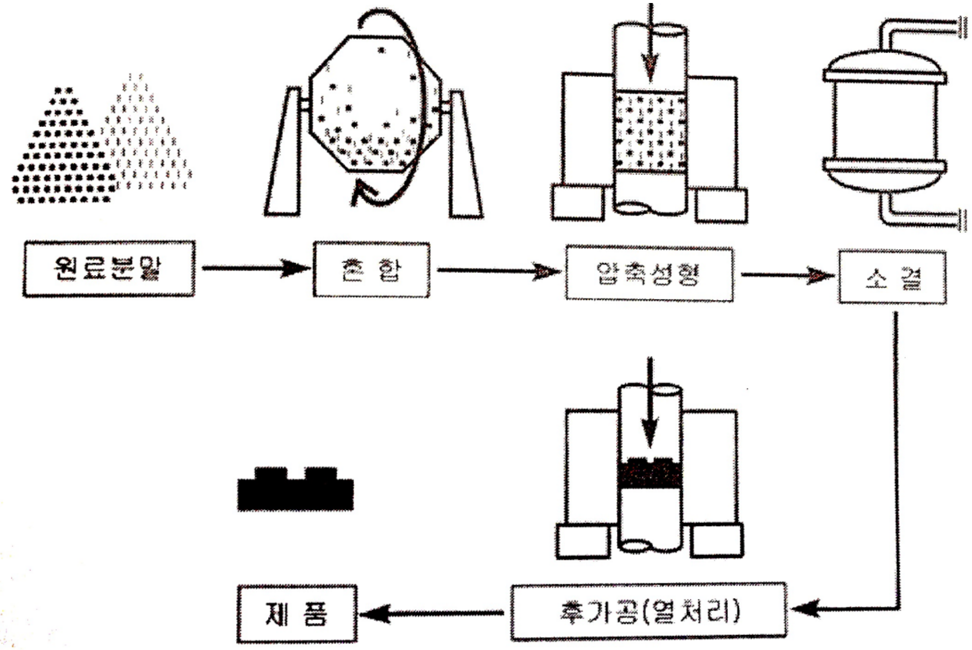
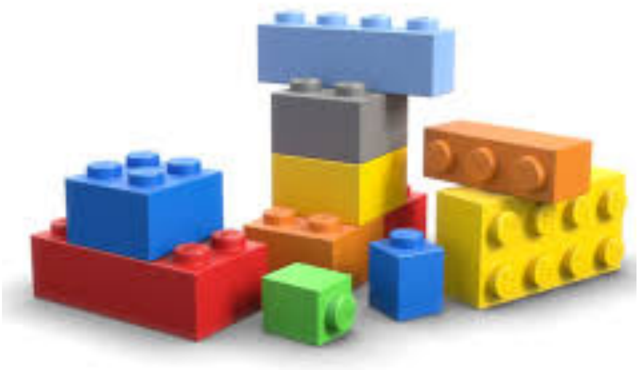


그림 4.2 분말성형의 일반적공정

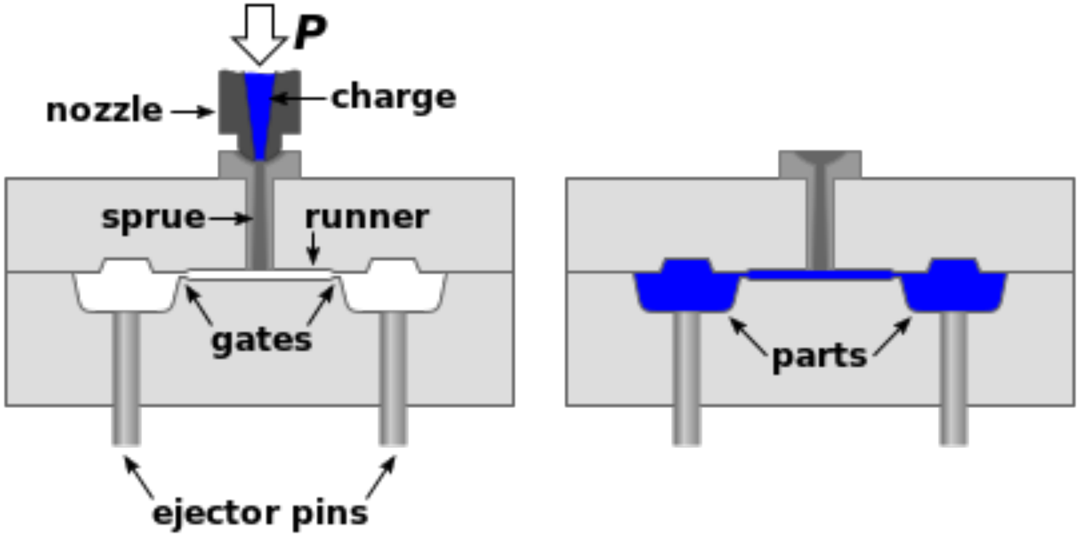
- https://youtu.be/O7U4HWjYcqo
- 재료가공학 – 서영섭 p93

사출 성형 (injection molding)

- Injection molding

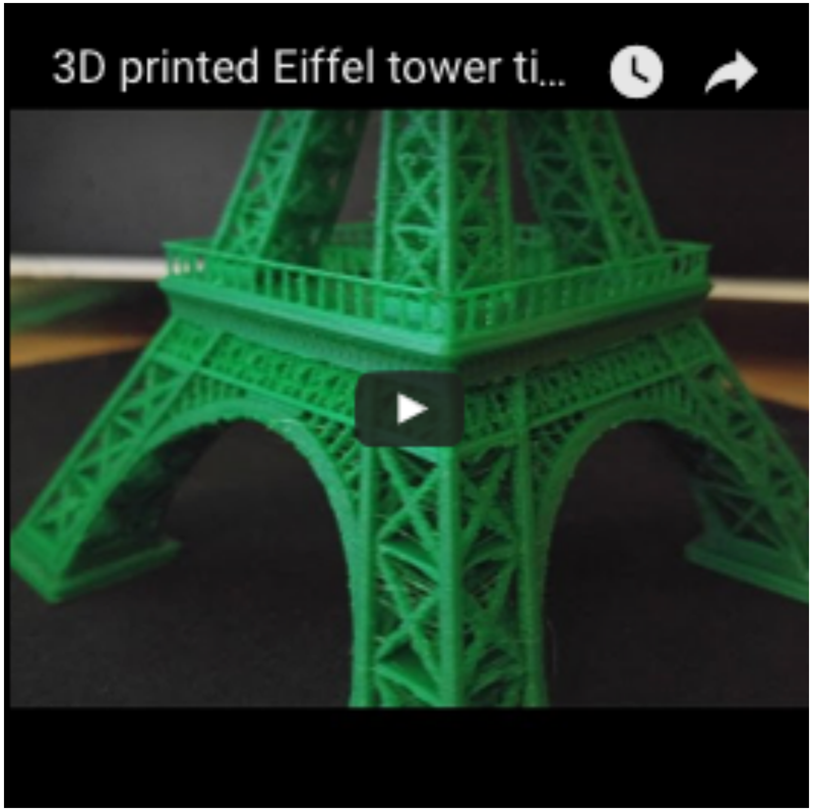


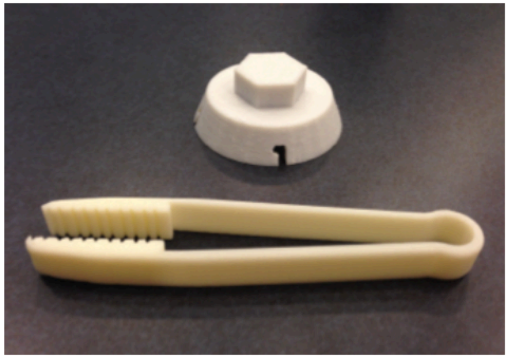
37sec



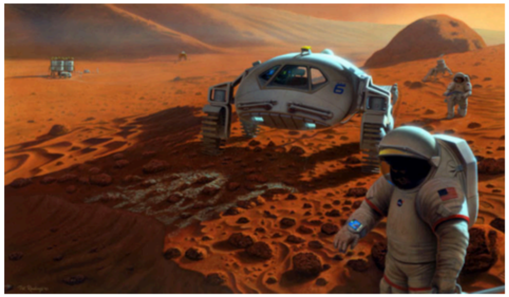
https://youtu.be/y1Zhpdx-XtA

Additive manufacturing (3D print)





The plastic tools above were printed with the Made In Space 3D printer and are representative of tools used by the space station crew.



Astronauts who pioneer the solar system and Mars will use additive manufacturing to print 3D supplies such as tools and equipment.

Q: 왜 NASA는 3D printer 연구에 관심이 있을까? Why does NASA study 3D printing technology?

https://youtu.be/FqQAjkZOBeY
https://www.nasa.gov/sites/default/files/files/3D_Printing-v3.pdf

소성 가공?

- 재료에 힘을 가해 원하는 형태로 가공하는 제조법. A manufacturing process in which external load is applied to the material to achieve the desired shape.
- Advantages:
  - 재료의 손실이 거의 없다 (no big loss of material).
  - 동일한 제품을 ‘대량’으로 생산하기에 적합 (adequate for mass production)

- Q1. 소성이란? What is plasticity?
- Q2. 탄성이란? What is elasticity?
- Q3. 소성가공의 단점?

소성 가공과 기계적물성

- 기계적 물성 (Mechanical Property)
- Q. 기계적 물성이란? (What is mechanical property? Stimuli and response?)
- Q. 기계적 물성의 종류, 그리고 측정 방법 (What types of MP? How to measure them? Name some examples)
- Q. 물리량? 힘, 변형 (Physical quantities? Force, deformation)
- Q. 기계적 물성을 나타내기에 적합한 물리량이 무엇일까? (What are the adequate physical quantities that may be useful when representing mechanical properties?)

물성과 물리 법칙

- Q. intensive physical quantity (세기 물리량) 과 extensive physical quantity (크기 물리량)을 설명할 수 있는가?
- Q. 크기에 의존하지 않은 물리량은 무엇이 있는가? (what are the physical quantities that are not dependent on the size of material?)

- 물성을 나타내기 위해서는 해당 물질의 '크기' (혹은 무게, 부피)에 의존하지 않은 물리량 (physical quantity)을 사용한다. We use size-independent physical quantities when represent a material property.

- 재료공학에서 물성을 표현하는 물리 법칙들은 대게 크기에 의존하지 않은 물리량들간의 관계를 나타낸다. In materials science, physical rules (laws) are based on the size-independent quantities.

응력 그리고 변형률 (stress and strain)

- Q. 왜 응력과 변형률을 배울까?
- Q. 한 물체가 가지는 응력과 변형률의 관계?

- 한 물체의 기계적 성질을 구성모델 (constitutive model)로 표현한다. 구성 모델은 물체에 작용한 응력에 대해 어떤 변형률로 반응이 나타나는지 표현해낸다 (혹은 vice versa). 많은 자연의 법칙이 그렇듯이 '수학' 이라는 언어로 표현한다.

- 금속이 가지는 기계적 성질은 구성 모델로 표현되고, 그 구성 모델들은 '수학'이라는 '언어' 로 쓰여져 있다.

- 앞으로 몇주간 금속의 기계적 성질을 표현하는데 가장 중요한 두 물리량, 응력(stress)과 변형률(strain)에 대해서 집중적으로 살펴본다.

Example: elasticity of metals

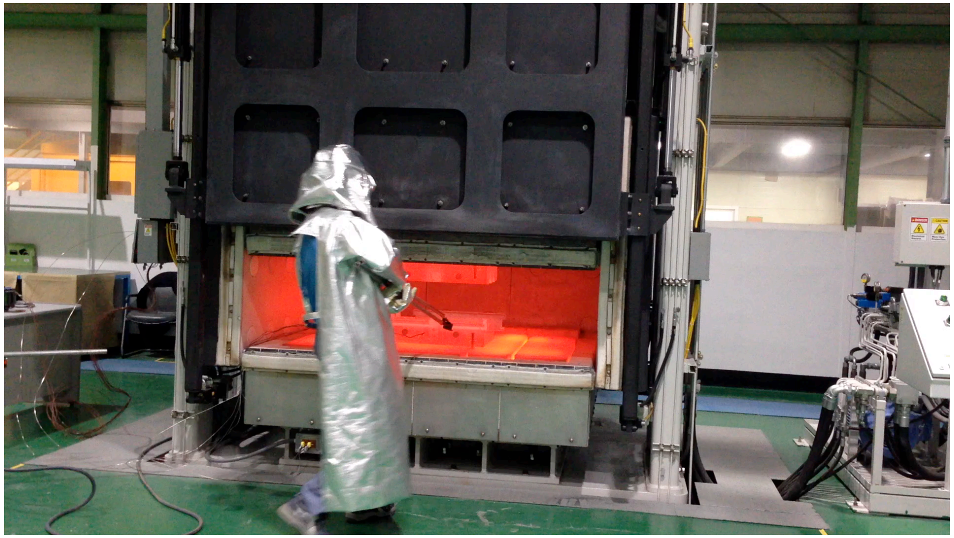
- In the elastic regime for a metal, the mechanical property can be understood by looking at the relationship between strain and stress. Notice that both strain and stresses are ‘intensive’ properties. The physical rule governed in this elastic reason is often called Hooke’s law, which shows that stress and strain is ‘linearly’ correlated.

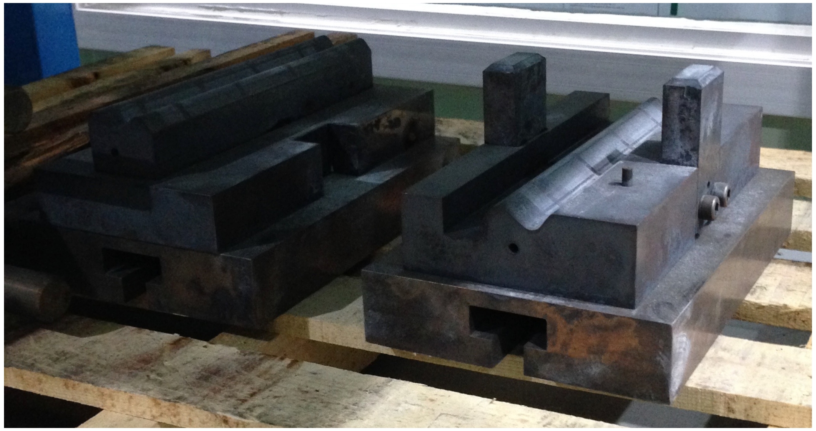
- What is the constitutive law in this example?

- Does elasticity mean the linearity between stress and strain?

창원과 소성 가공 (Changwon and Metal forming)

- 창원의 지역 특수성
- 예: 삼우공업
  - 다양한 Titanium 합금 소재 성형 솔루션이 필요.
  - 합금 소재의 기계적 물성을 이해하는 전문성을 갖춘 인재가 필요.





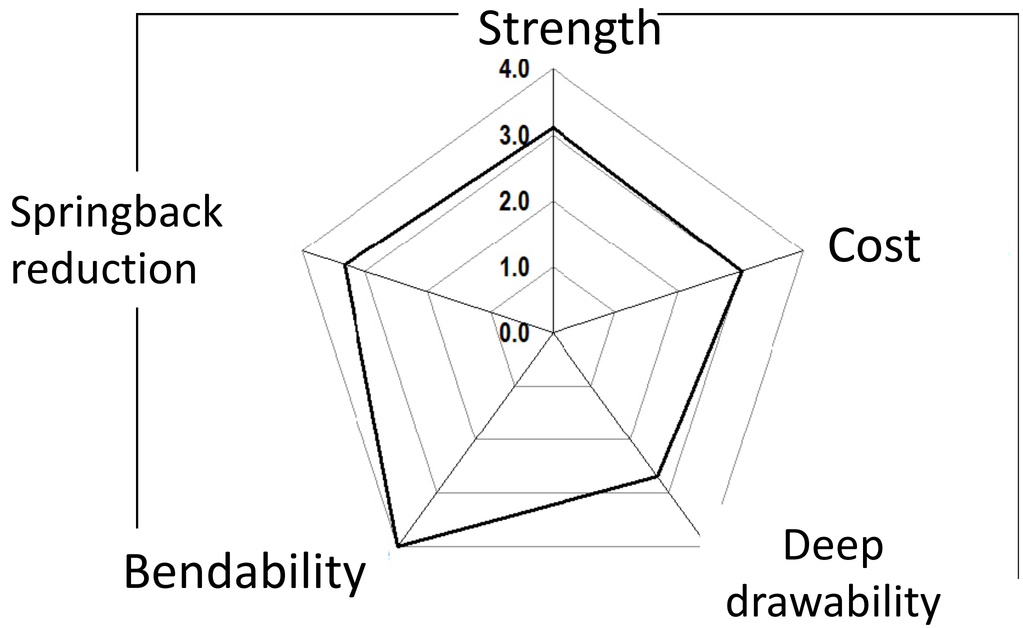
Okay, there are solutions already. Why should we learn metal plasticity?

- Engineers always look for cost reduction – that's the key.
- Cost reduction requires prevention of 'waste'.
- We always push towards the limits (critical points) – although we should think about 'safety' lines.
- Examples: not everyone can afford to having an expensive car.

DeLorean

- What can be optimized for the example of 삼우공업

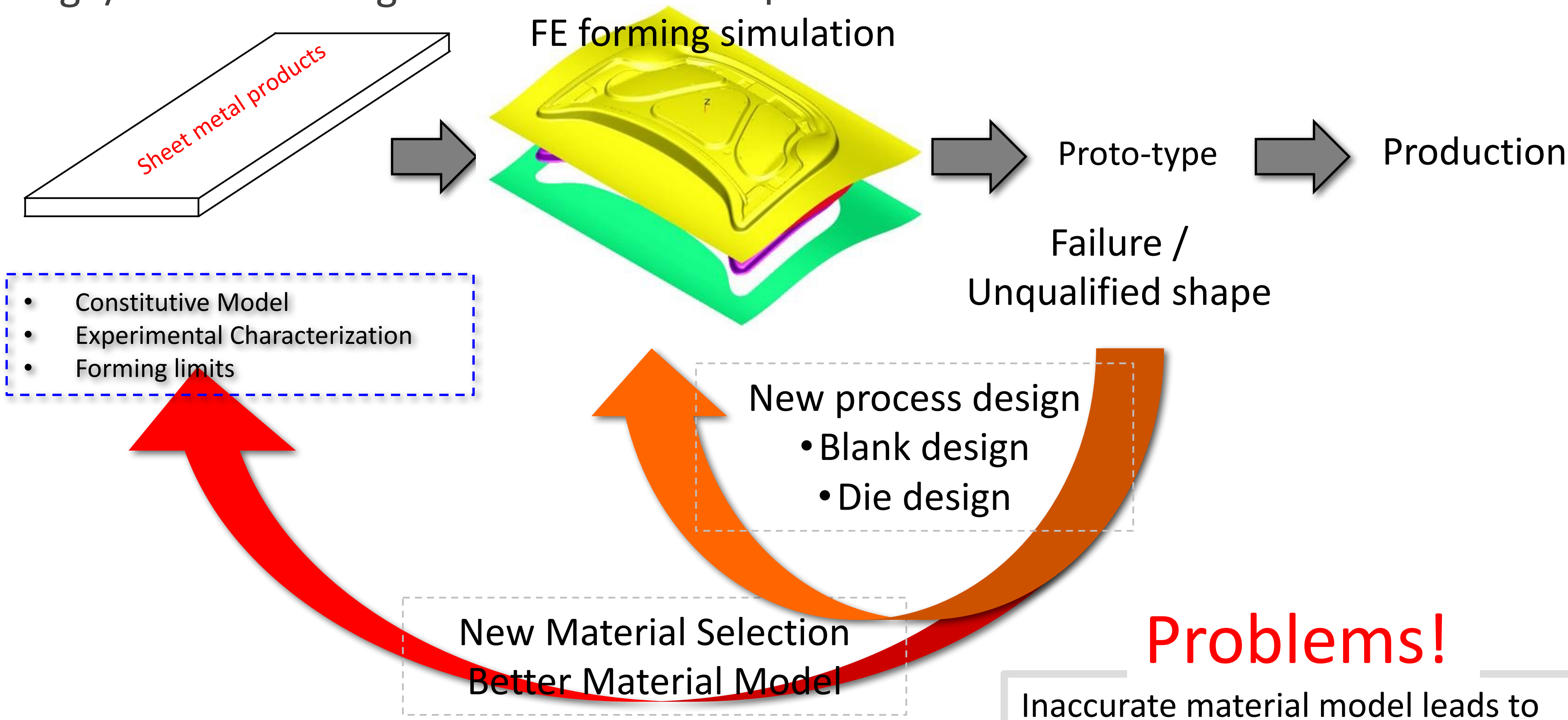
Optimization of multiple properties



- It is generally the case that any given material must meet minimum requirements for multiple properties.
- Therefore it is not feasible to optimize one property at the expense of all others.
- On the "spider diagram" example, one can visualize this requirement by seeing that the polygon must have vertices at some distance from the origin along every axis.

Sheet metal forming procedure

Design/manufacturing of automotive component



Problems!

Inaccurate material model leads to
* Delayed production
* Tooling revision
* Rejection of unqualified parts
* $50 M wasted (2003)

- USCAR (Big 3 Automaker Consortium) (2003)
- Innovation in Sheet Metal Forming: Workshop Summary Report (2015)

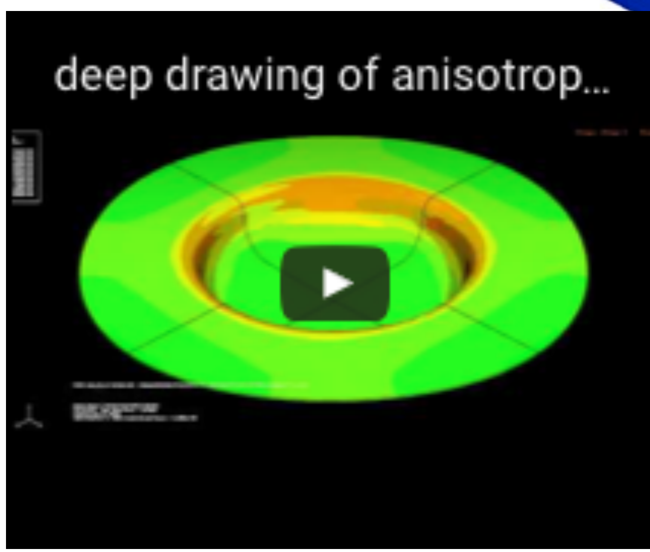
최신 소성 가공 연구 동향

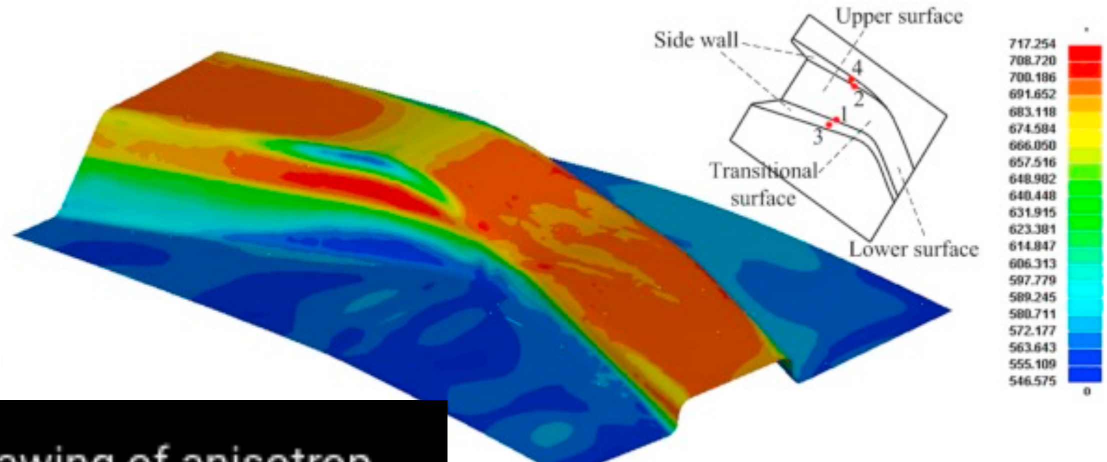
- 기계, 자동차, 군수 등 다양한 제조 산업 업체
- 소성 가공 커뮤니티에서의 최신 연구 동향에 따르면 기계 및 열적 물성을 총체적으로 고려한 솔루션이 널리 요구되고 있다.
- 또한 컴퓨터를 활용한 예측 시뮬레이션의 개발과 이용이 날로 확장되고 있다.
- 과거에 소성가공은 기계 전공이 주였다면 현재는 복잡해지는 금속 소재의 특성을 이해하는 재료 전문 분야로 확장중.
- 지난 10년간 나의 연구 주제: 금속 소재의 미세 구조 (microstructure)가 물질의 기계적 물성에 끼치는 영향 파악. 그 반대로 (an inverse approach), 특정 기계적 물성을 향상 시키기위해서 어떤 미세 구조를 가져야 하는가?

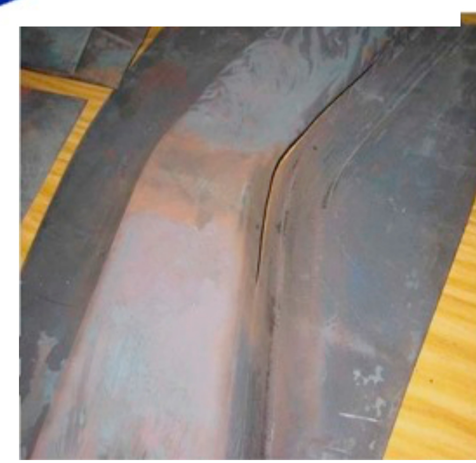
최신 소성 가공 연구 동향

- 향후 연구주제: 버튼 하나로 제공되는 재료 맞춤형 소성 가공 예측 프로그램 개발

Grain size, CRSS control, crystallographic texture, single crystal structure, dislocation density …







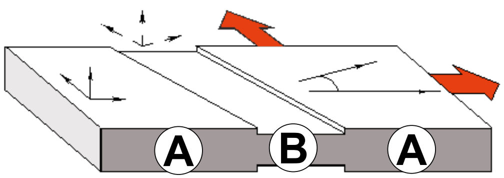
Chang et al., Applied Thermal Engineering 99, 25, 2016 p419-428

금속 판재의 성형성 측정과 예측

성형성 예측 모델의 개발 과정

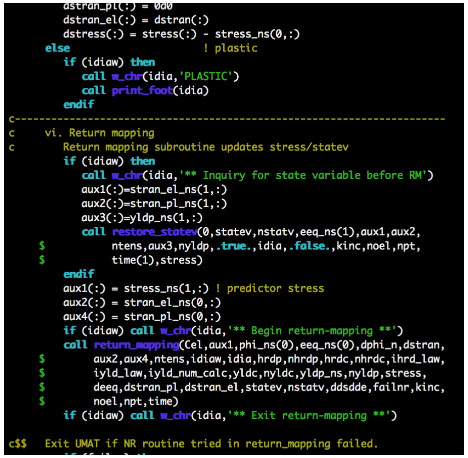
구성방정식 개발
(하중/변형률 관계 규명)

$$\dot{\boldsymbol{\varepsilon}} = \dot{\gamma}_0 \sum_{s} \mathbf{m}^{s} \left(\frac{\mathbf{m}^{s} : \boldsymbol{\sigma}}{\tau_c^{s}} \right)^{n} \operatorname{sgn}(\mathbf{m}^{s} : \boldsymbol{\sigma})$$



$$L_{ij}^{(A)} = c \cdot \begin{bmatrix} 1 & L_{12}^{(A)}/c & 0 \\ 0 & \rho & 0 \\ 0 & 0 & -(\rho+1) \end{bmatrix} \mathbf{e}_i^{\mathrm{lab}} \otimes \mathbf{e}_j^{\mathrm{lab}}$$

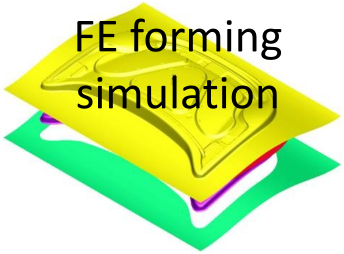
컴퓨터 SW 개발
(User Material / FE)



```
            dstran_pl(:) = 0d0
            dstran_el(:) = dstran(:)
            dstress(:) = stress(:) - stress_ns(0,:)
         else                          ! plastic
            if (idiaw) then
               call w_chr(idia,'PLASTIC')
               call print_foot(idia)
            endif
c-----------------------------------------------------------------------
c        vi. Return mapping
c           Return mapping subroutine updates stress/statev
            if (idiaw) then
               call w_chr(idia,'** Inquiry for state variable before RM')
               aux1(:)=stran_el_ns(1,:)
               aux2(:)=stran_pl_ns(1,:)
               aux3(:)=yldp_ns(1,:)
               call restore_statev(0,statev,nstatv,eeq_ns(1),aux1,aux2,
     $              ntens,aux3,nyldp,.true.,idia,.false.,kinc,noel,npt,
     $              time(1),stress)
            endif
            aux1(:) = stress_ns(1,:) ! predictor stress
            aux2(:) = stran_el_ns(0,:)
            aux4(:) = stran_pl_ns(0,:)
            if (idiaw) call w_chr(idia,'** Begin return-mapping **')
            call return_mapping(Cel,aux1,phi_ns(0),eeq_ns(0),dphi_n,dstran,
     $           aux2,aux4,ntens,idiaw,idia,hrdp,nhrdp,hrdc,nhrdc,ihrd_law,
     $           iyld_law,iyld_num_calc,yldc,nyldc,yldp_ns,nyldp,stress,
     $           deeq,dstran_pl,dstran_el,statev,nstatv,ddsdde,failnr,kinc,
     $           noel,npt,time)
            if (idiaw) call w_chr(idia,'** Exit return-mapping **')

c$$   Exit UMAT if NR routine tried in return_mapping failed.
```

컴퓨팅 수치해석



물성 모델 개발에서의
다양한 접근법 가능

현상학적 모델
(Phen. Model)

- 상대적으로 빠른 전산 속도
- Macro 기계물성 (예: R-value, Yield stress …)

미세구조기반
미세역학모델

- 상대적으로 느린 전산 속도
- Micro 기계물성 (예: slip/twin system, texture …)

Microstructural parameters, Properties

Properties

- Strength
- Toughness
- Conductivity
- Corrosion Resistance
- Piezoelectric strain
- Dielectric constant
- Magnetic Permeability
- **Formability**

Microstructural Parameters

- Grain size
- Grain shape
- Phase structure
- Composite structure
- Chemical composition (alloying)
- Crystal structure
- Defect structure (e.g. porosity)

Microstructural parameters, properties

- Yes, when we study the plasticity of metals, we now should consider the microstructure of the material of interest
- Q. What is microstructure?
- A. Microstructure = internal structure

Biology was revolutionized when Leeuwenhoek and others started to use microscopes to look at the internal structure of plants. They were able to relate many characteristics of plants to their cell structure, for example.

Similarly, Sorby† was one of the first to make cross-sections of materials such as iron and examine them in the microscope, so that he could relate properties to structure.

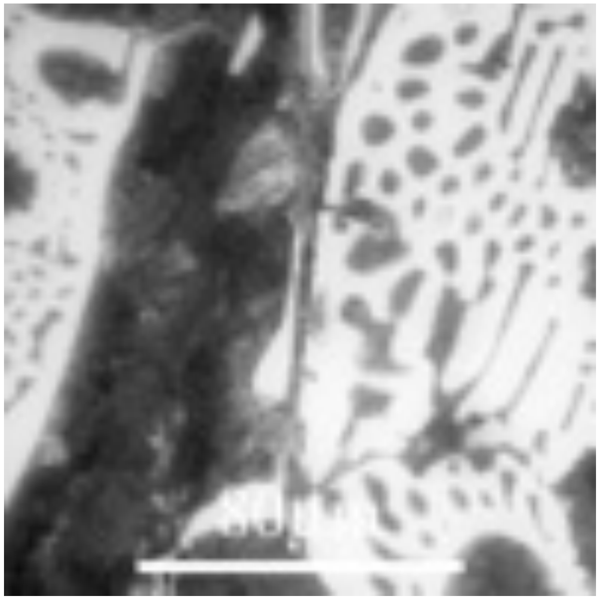
* http://www.ucmp.berkeley.edu/history/leeuwenhoek.html

† http://www.shu.ac.uk/sorby/hcsorby.shtml

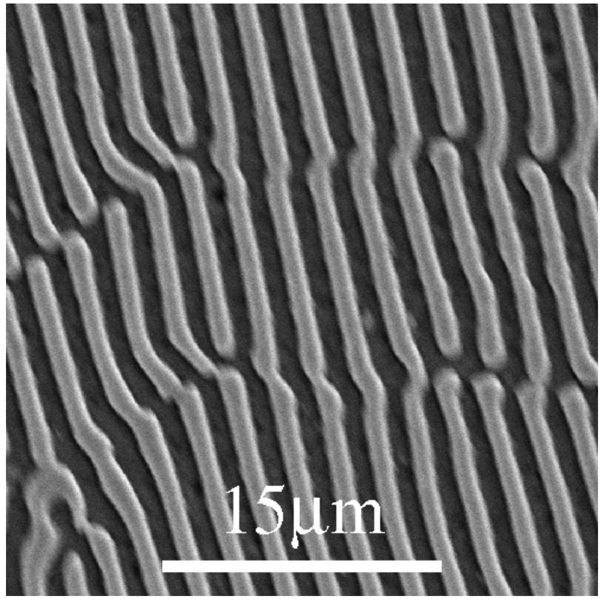
What is microstructure?

- Microstructure originally meant the structure inside a material that could be observed with the aid of a *microscope*.
- In contrast to the crystals that make up materials, which can be approximated as collections of atoms in specific packing arrangements (*crystal structure*), *microstructure* is the collection of *defects* in the material.
- What defects are we interested in? Interfaces (both grain boundaries and interphase boundaries), dislocations (and other line defects), and point defects.
- Since the invention of prefixes for units, the *micrometer* (1 µm) happens to correspond to the wavelength of light. Light, obviously is used to form images in a light/optical microscope. Thus *microstructure* has come to be accepted as those elements of structure with length scale of order 1 µm.
- Since we commonly examine materials in the microscope, we generally observe *grains* as crystallites in *polycrystals*, separated by *grain boundaries*.

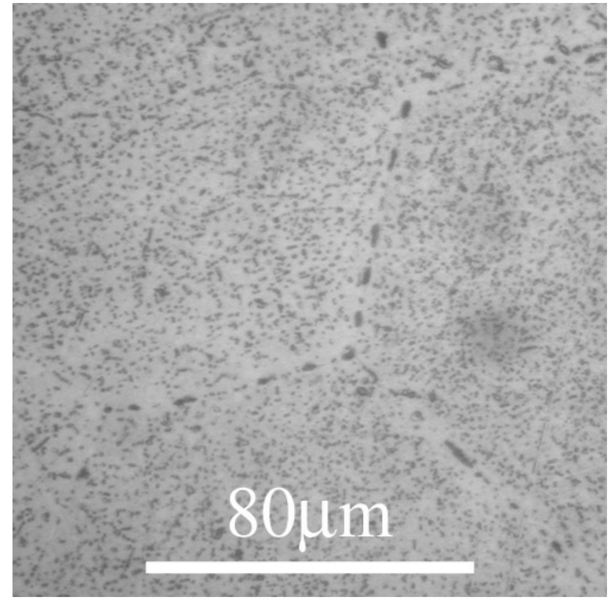
If you look ‘inside’



Fe-C-X; Hypoeutectic white cast iron

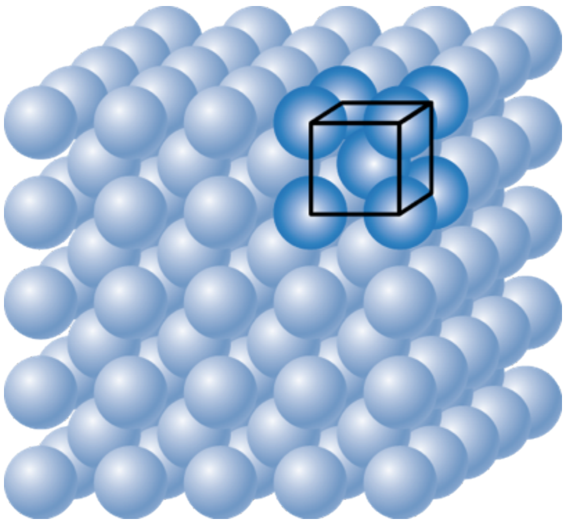


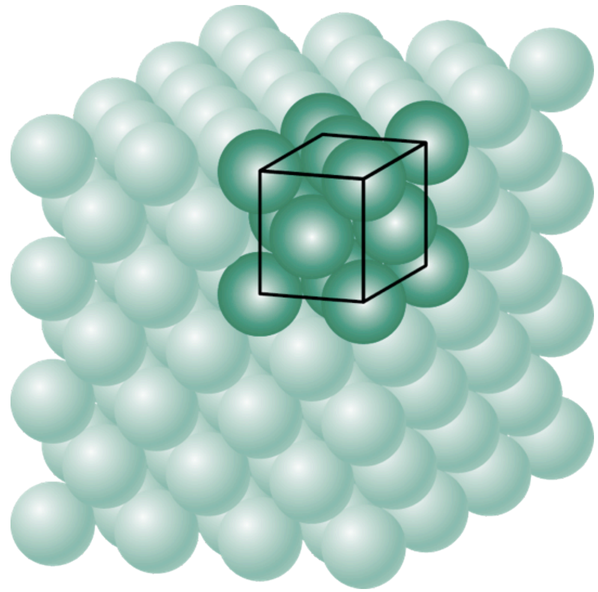
Al 67wt% Cu 33wt%, Eutectic alloy

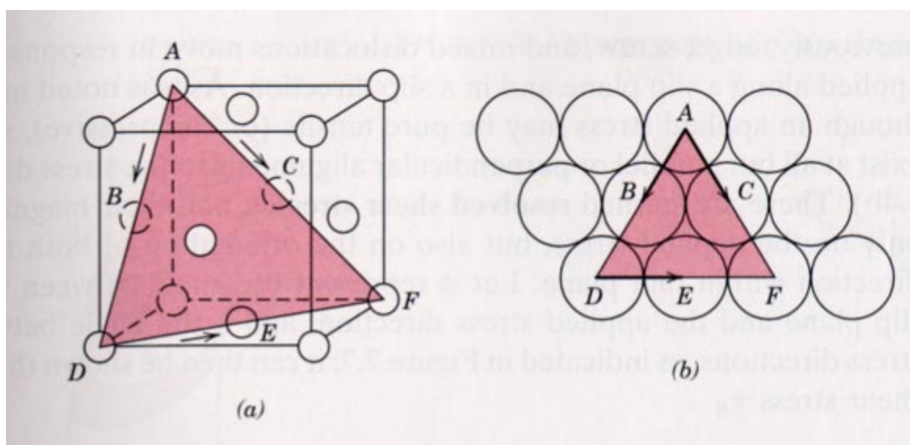


Al 96wt% Cu 4wt% Precipitates

If you look ‘inside’ (crystal structure)







If you look ‘inside’ (crystal structure)

- HCP is more ‘anisotropic’ than cubic structures.

Basal
(0002) <2 -1 -1 0>

Prism
{0 -1 1 0}<2 -1 -1 0>
Also:
(2 -1 -1 0)

Pyramidal (c+a)
(1 0 -1 1) <1 -2 1 3>
Pyramidal (a)
(1 0 -1 1) <1 -2 1 0>

Pyramidal
(1 0 -1 2)

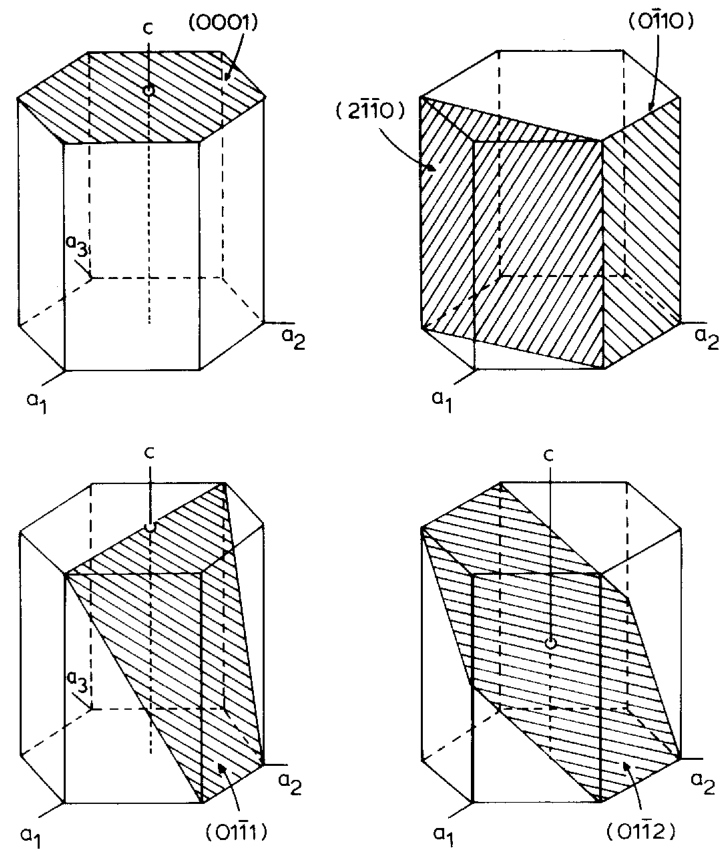


FIG. IV-5—*Some important planes in the hcp system and their Miller-Bravais indices.*

Berquist & Burke: Zr alloys

Slip systems

The slip systems for FCC, BCC and hexagonal crystals are:

Metals	*Slip Plane*	*Slip Direction*	*Number of Slip Systems*
	Face-Centered Cubic		
Cu, Al, Ni, Ag, Au	$\{111\}$	$\langle 1\bar{1}0\rangle$	12
	Body-Centered Cubic		
α-Fe, W, Mo	$\{110\}$	$\langle \bar{1}11\rangle$	12
α-Fe, W	$\{211\}$	$\langle \bar{1}11\rangle$	12
α-Fe, K	$\{321\}$	$\langle \bar{1}11\rangle$	24
	Hexagonal Close-Packed		
Cd, Zn, Mg, Ti, Be	$\{0001\}$	$\langle 11\bar{2}0\rangle$	3
Ti, Mg, Zr	$\{10\bar{1}0\}$	$\langle 11\bar{2}0\rangle$	3
Ti, Mg	$\{10\bar{1}1\}$	$\langle 11\bar{2}0\rangle$	6

Also: Pyramidal (c+a) (1 0 -1 1) <1 -2 1 3>

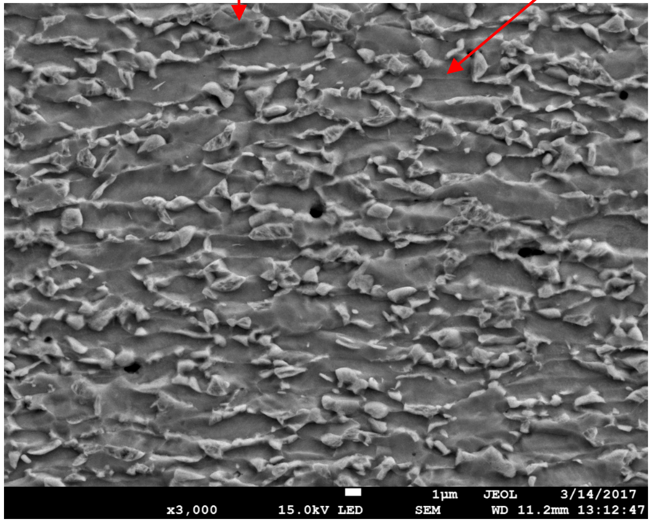
Note: In the case of FCC crystals we can see in the table that there are 12 slip systems. However if forward and reverse systems are treated as independent, there are then 24 slip systems.

If you look ‘inside’ (multiphase)

Modern steels are often multiphase alloys

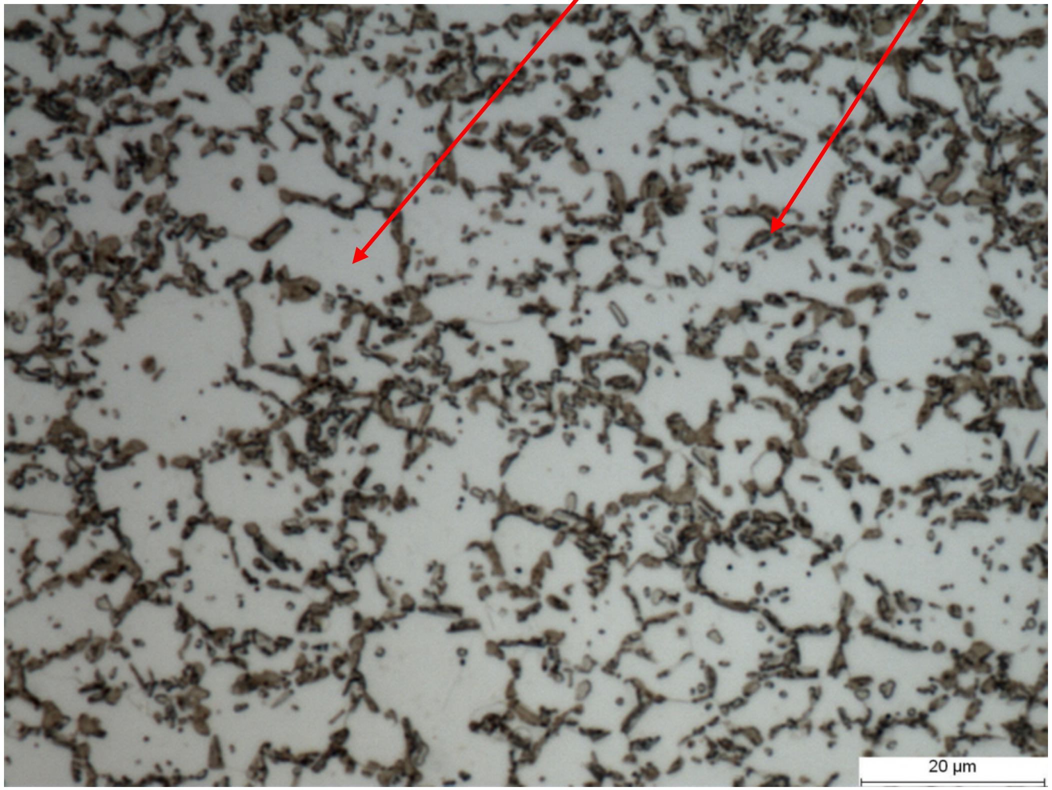
Martensite

Ferrite



ferrite

martensite



Important microstructural features

Examples of quantitative microstructural parameters:

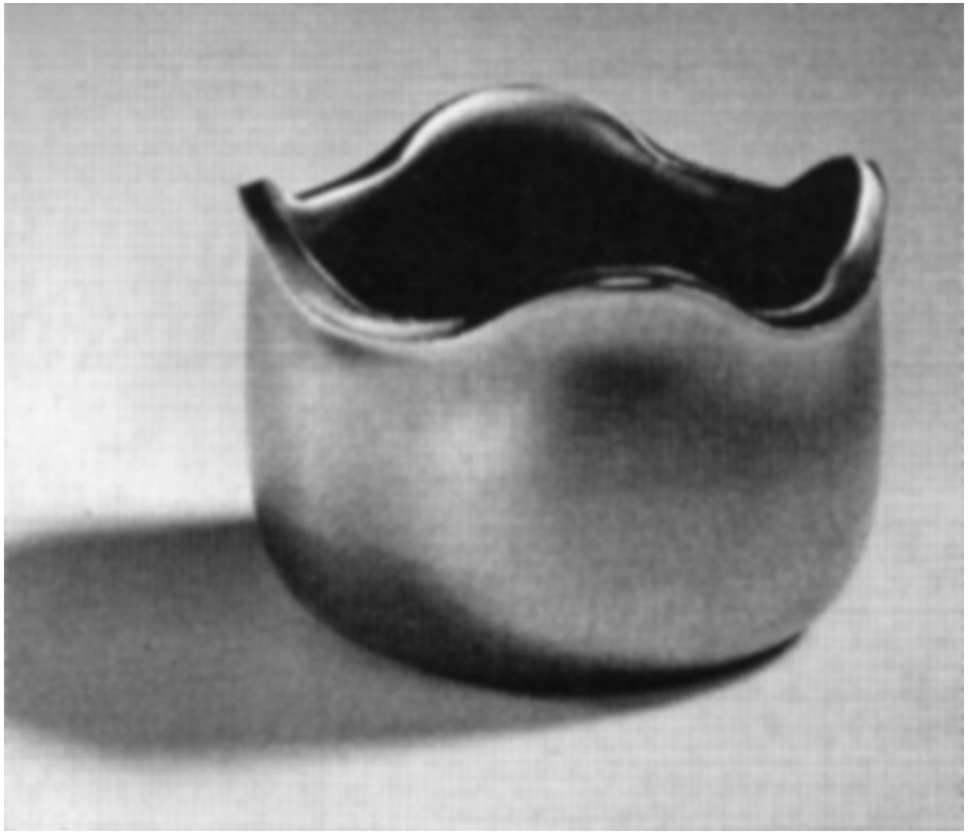
- Grain size
- Void fraction
- Aspect ratio of second phase particles or grains
- Crystal orientation distribution (crystallographic texture)

Anisotropy

- All crystal structure is intrinsically anisotropic.
- Q: Should polycrystalline materials consisting of many crystals anisotropic?
- Q: If not, what makes polycrystal material anisotropic?

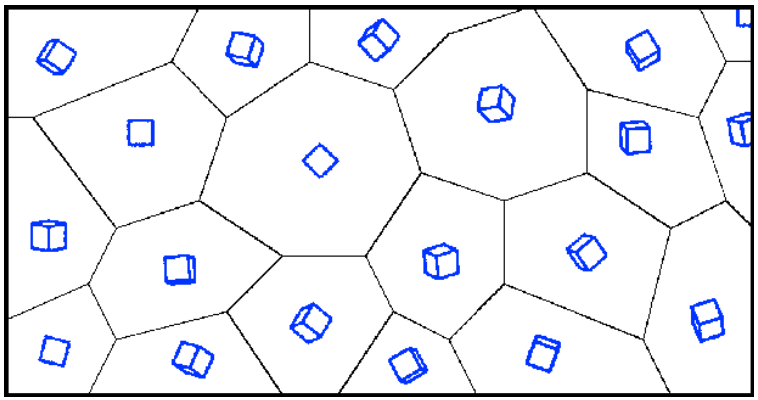
Plastic anisotropy

Figure shows example of a cup that has been deep drawn. The plastic anisotropy of the aluminum sheet resulted in non-uniform deformation and "ears."



Randle, Engler, p.340

Grain orientation



Blue cubes denote unit cells representative of the pertaining grain bounded by gray lines (Q. What is the gray lines here?)

An orientation is a 'relative term'.
상대적인 개념. 기준(reference)이 되는 방향이 갖춰져야 한다.

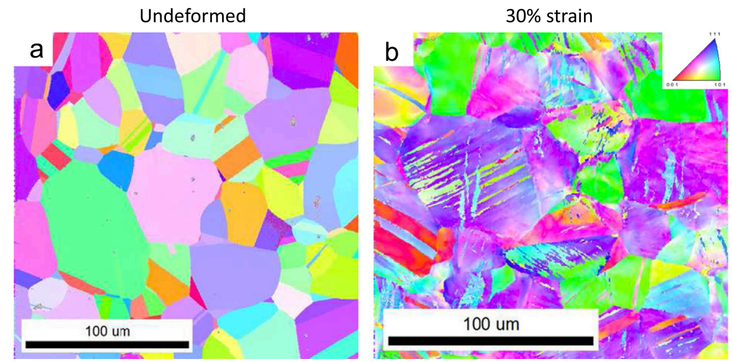
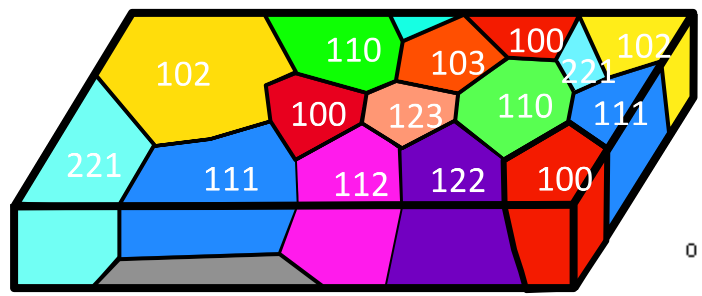
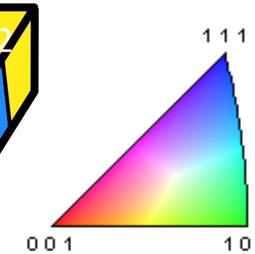


Fig. 1. EBSD orientation map of 304 stainless steel sheet at tensile strains of (a) 0% (undeformed) and (b) 30%.



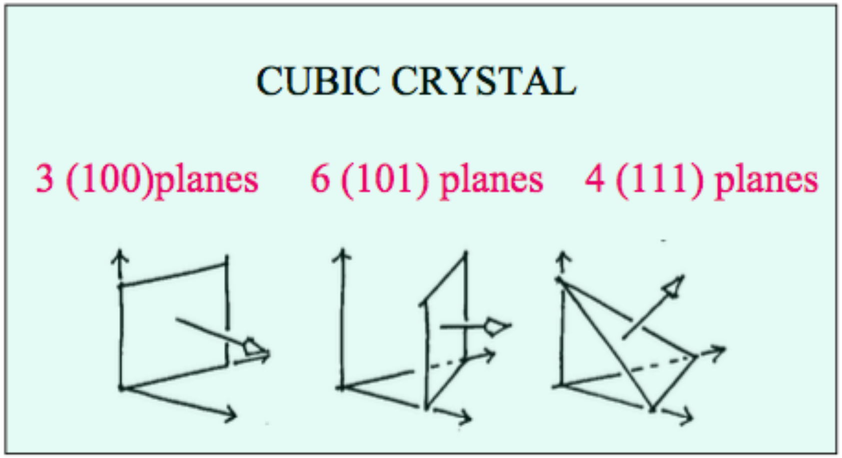


Q. 위 inverse pole figure의 orientation은 color-map으로 표현된다. 사용된 기준은 무엇일까?

** H Wang, Y Jeong, B Clausen, Y Liu, RJ McCabe, F Barlat, CN Tome, MSEA 649, 2016*

Pole figure and inverse pole figure

X-ray diffraction
Q. Explain Bragg's law
Q. What is Monochromatic X-ray?



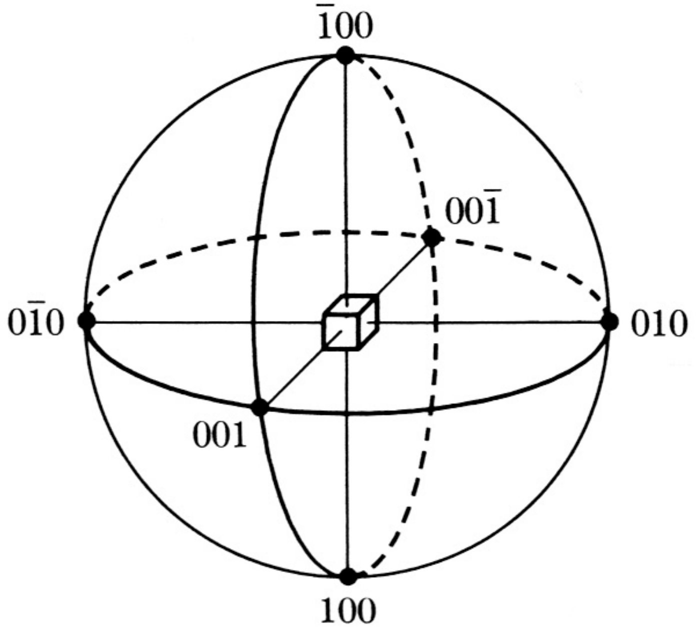
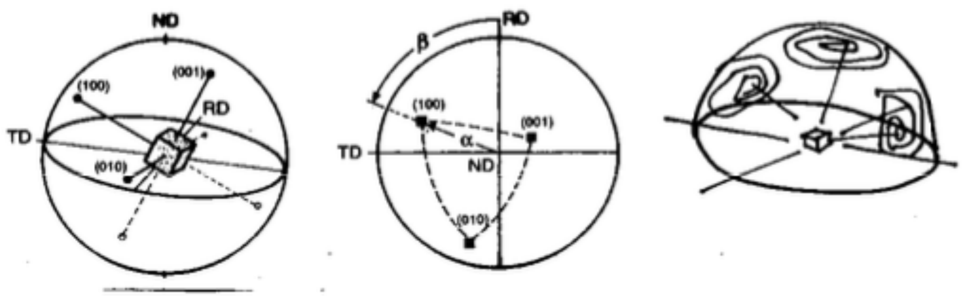
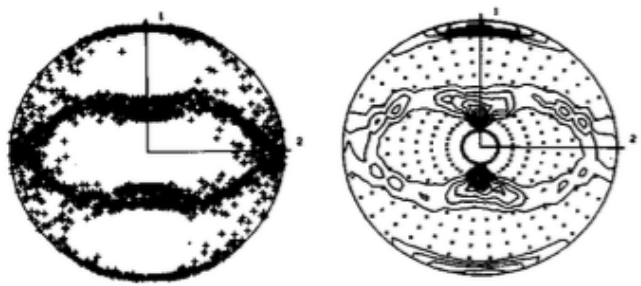


Fig. 2–25 {100} poles of a cubic crystal.

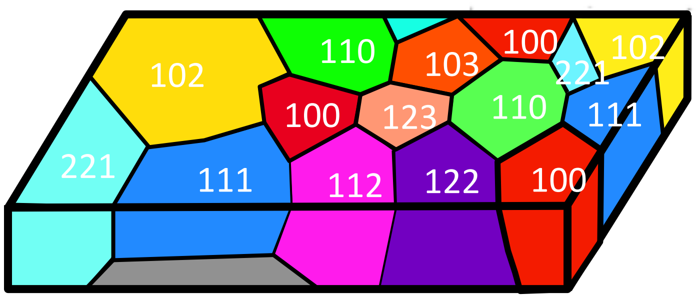
Difference between Inv. PF and PF

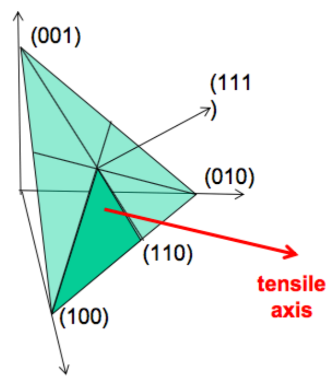
- Relativity. What is the reference and what do you want to visualize.

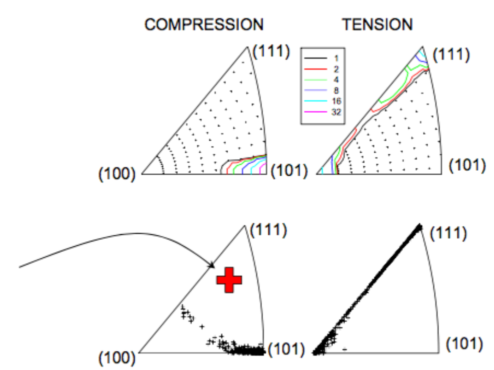




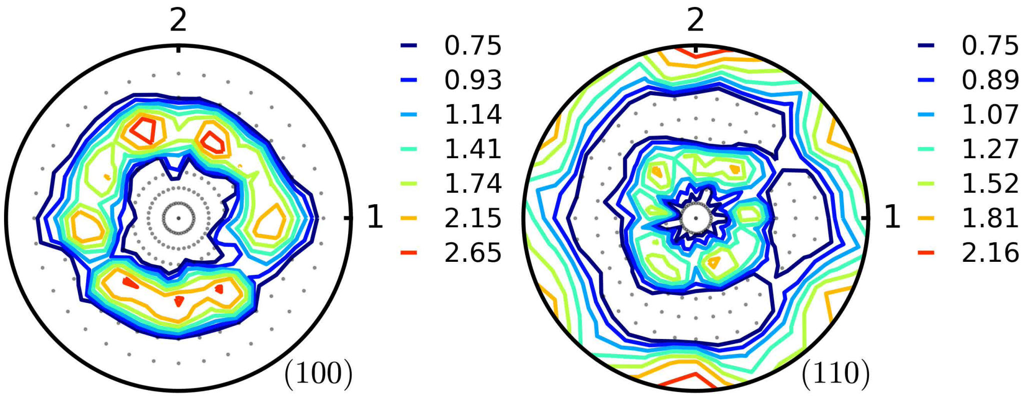
(111) pole figure of IF steel after 80% rolling reduction

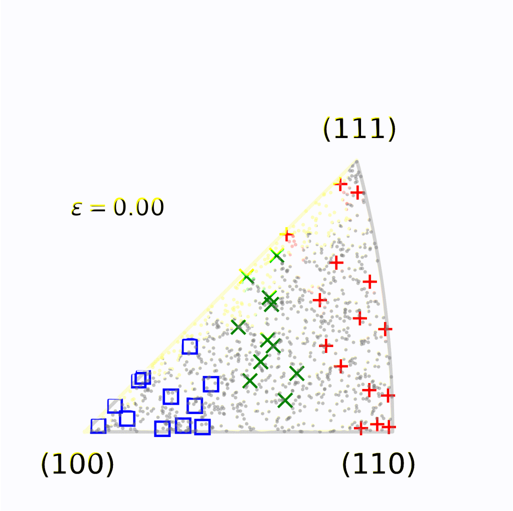






Evolution of texture





Calculated using viscoplastic self-consistent model and visualized by UPF package.

Recap

- Pros and cons of metal forming
- How polycrystalline material can be ‘isotropic’?
- What is crystallographic texture?
- What is inverse pole figure and pole figure?
- Can we have a type of new material that is best for everything? If not, why?

References and acknowledgements

- References.
- Acknowledgements
  - Some of the slides are based on the slides of prof. A.D. Rollett @ Carnegie Mellon University. He kindly permitted the reuse of his slides.
  - Some images presented in this lecture materials were collected from Wikipedia.