

非晶物理和材料的新进展

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内 容

一、非晶材料和物理发展历史、制备、特点、应用

二、科学问题

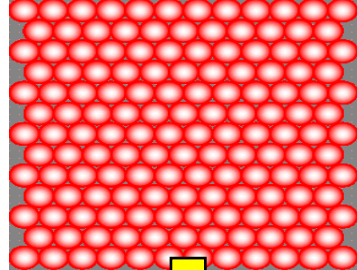
三、研究进展

四、应用

一、非晶材料和物理发展历史、制备、特性、应用

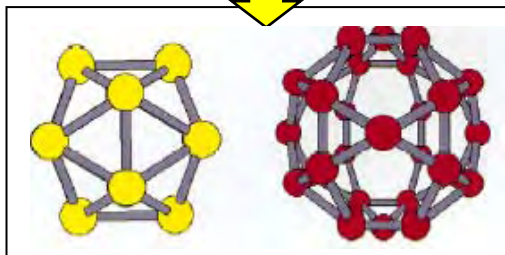
1-100 μm

晶体



点阵模型，能带理论，位错理论等

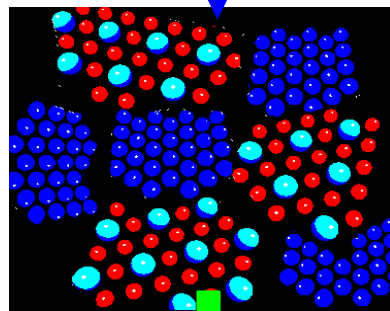
准晶



五次对称性

1-100 nm

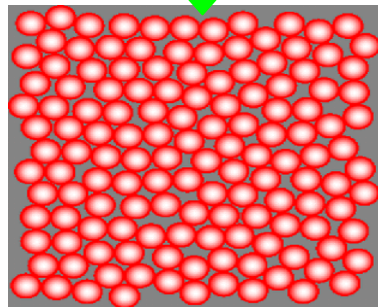
纳米晶



表征、性能，合成

亚纳米 < 1nm

非晶

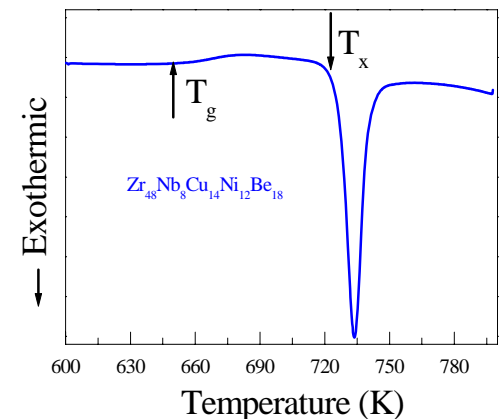
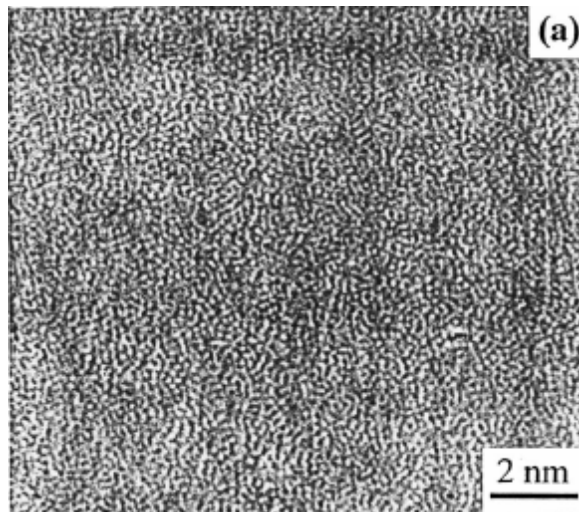
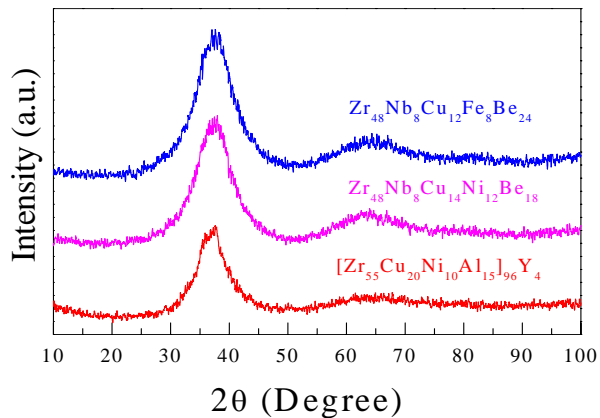
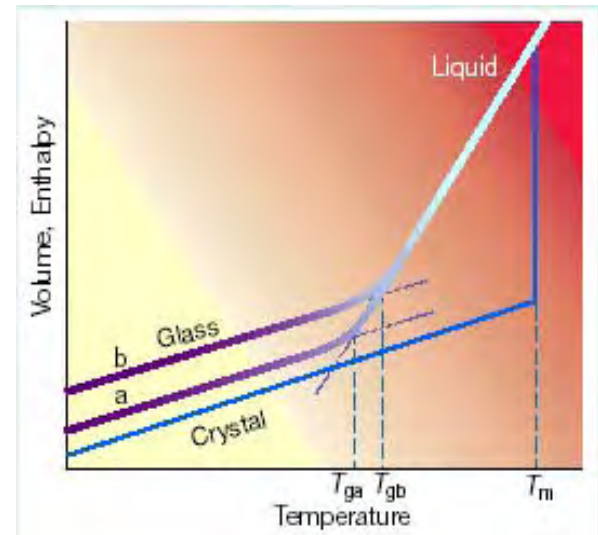


结构，合成，结构与性能关系 ???

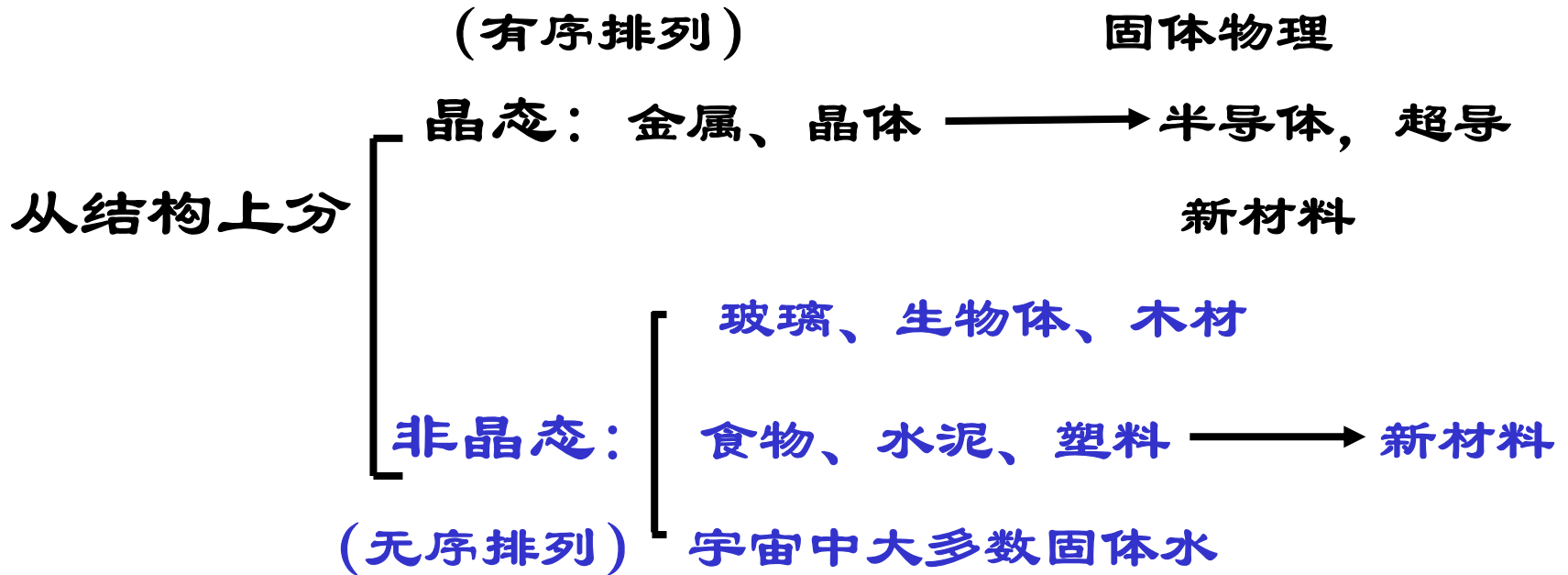
长程无序

非晶特征

- 1、长程无序，短程有序，衍射图样是弥散的晕环
- 2、亚稳态，温度或压力升高到一定值会发生晶化
- 3、宏观性能的各向同性
- 4、没有确切熔点
- 5、具有玻璃转变温度点 T_g



非晶或玻璃材料



- 天然非晶材料很早就被人类利用
- 玻璃为科学的发展作出极大的贡献
- 塑料的出现

玻璃是人类最早使用的重要材料之一

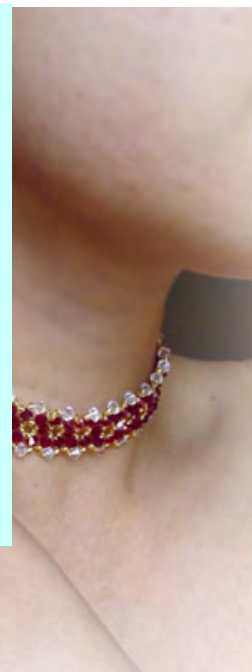
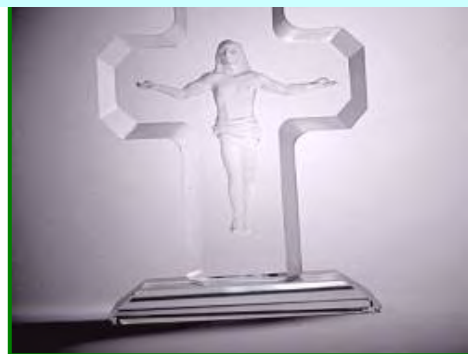
公元前2200，古伊朗人发明**玻璃**，被美国金属学会评为**材料史上10个“最伟大材料事件之一”**。

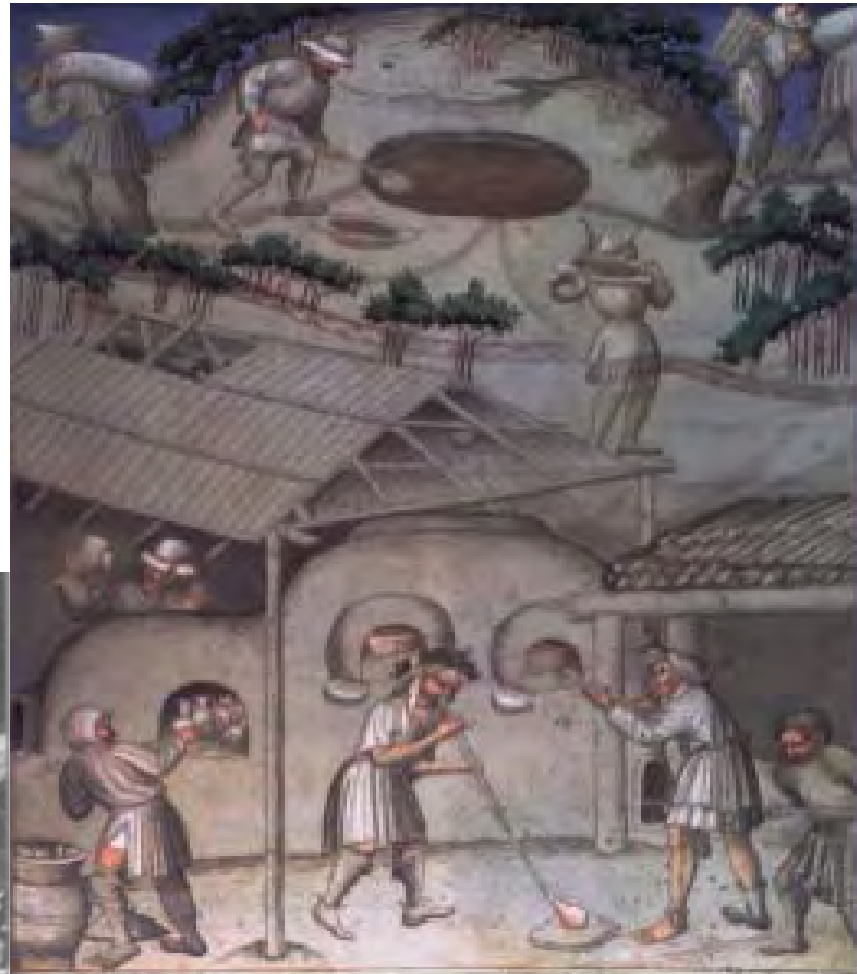
这也是继陶瓷之后第二种非金属材料

玻璃材料

优点：高强度，不导电等

缺点：脆性







春秋中期：
500-600 BC



▲ 越王勾践剑



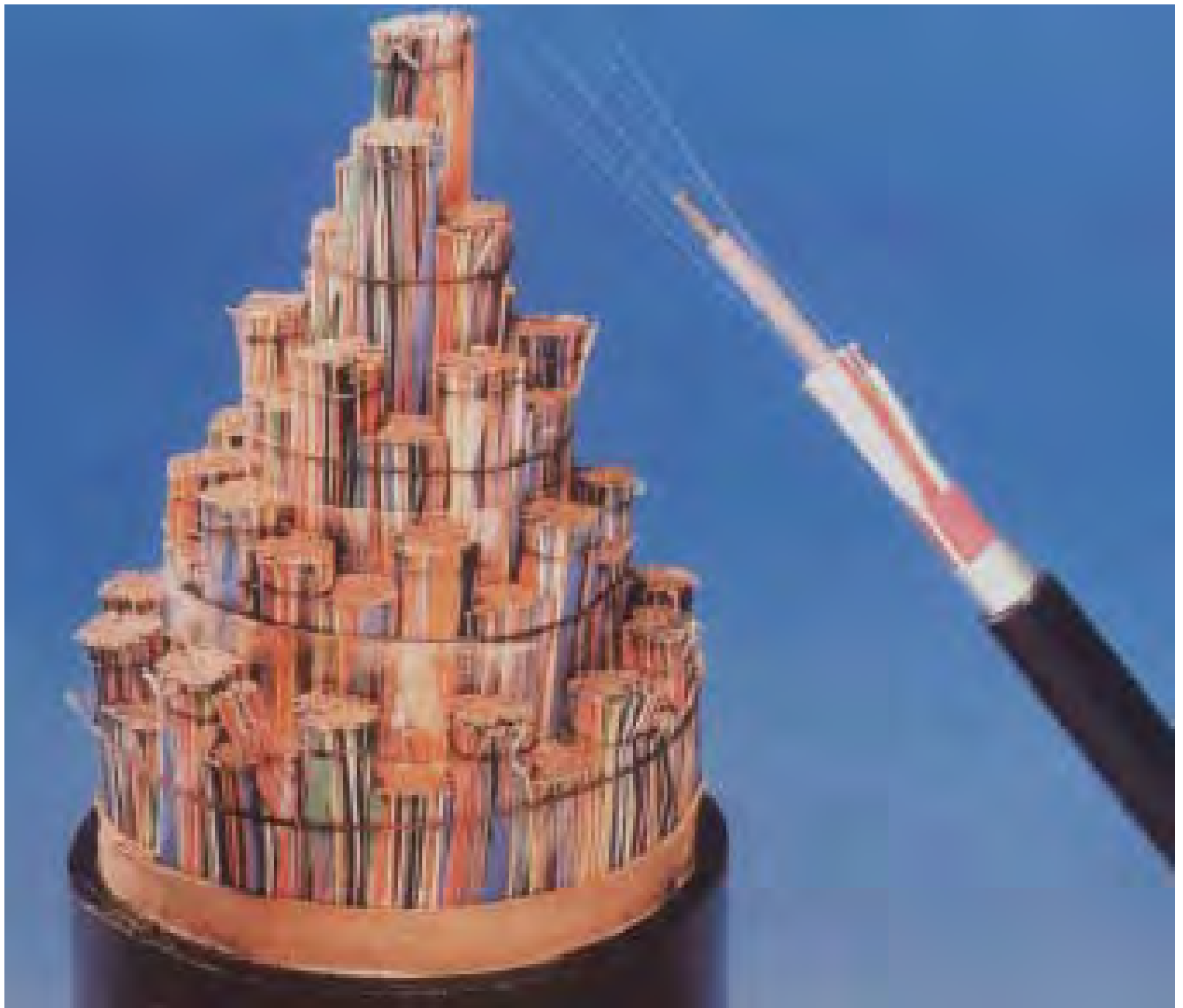
隋唐时期：夜光杯

越王勾践剑

玻璃在人类生活、科研中发挥重要作用









**金属材料作为应用最广泛的材料之一，
它的进展将带来巨大的经济效益**

**每个易拉罐节约1分钱， 全世界每年消
耗2000亿个易拉罐， 节约20亿元！**

金属材料

优点：良好的塑性、加工等

**缺点：加工制备高能耗、高污
染，低强度**

发现新材料是人类永久的追求

合金 → 玻璃化 → 新特性、应用

结合金属和玻璃的特性

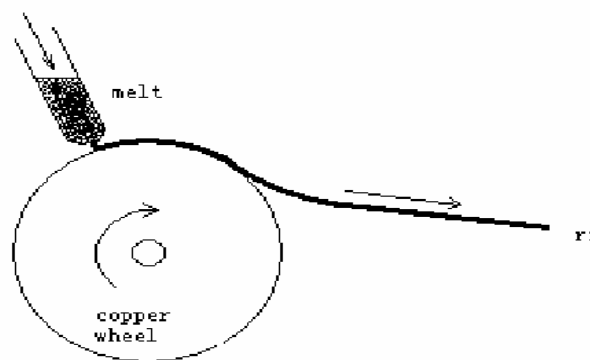


金属玻璃 (非晶合金)

- 丰富固体物理、材料科学理论和知识
- 推动其它学科发展
- 发展新材料的新途径

在各种不同化学键的材料中金属最难非晶化
虽然玻璃材料古老，但金属玻璃只有几十年的历史

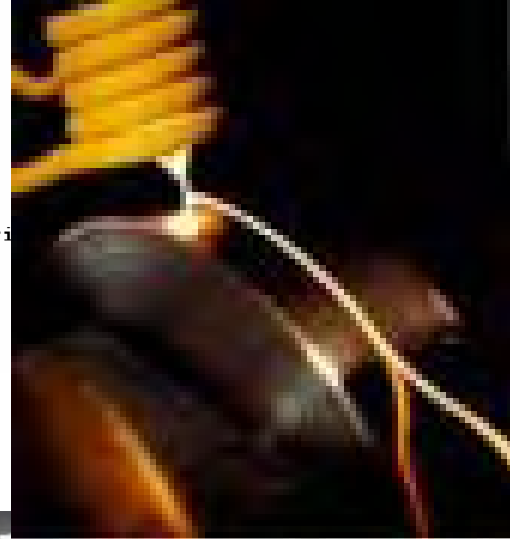
第一次突破 (1960)



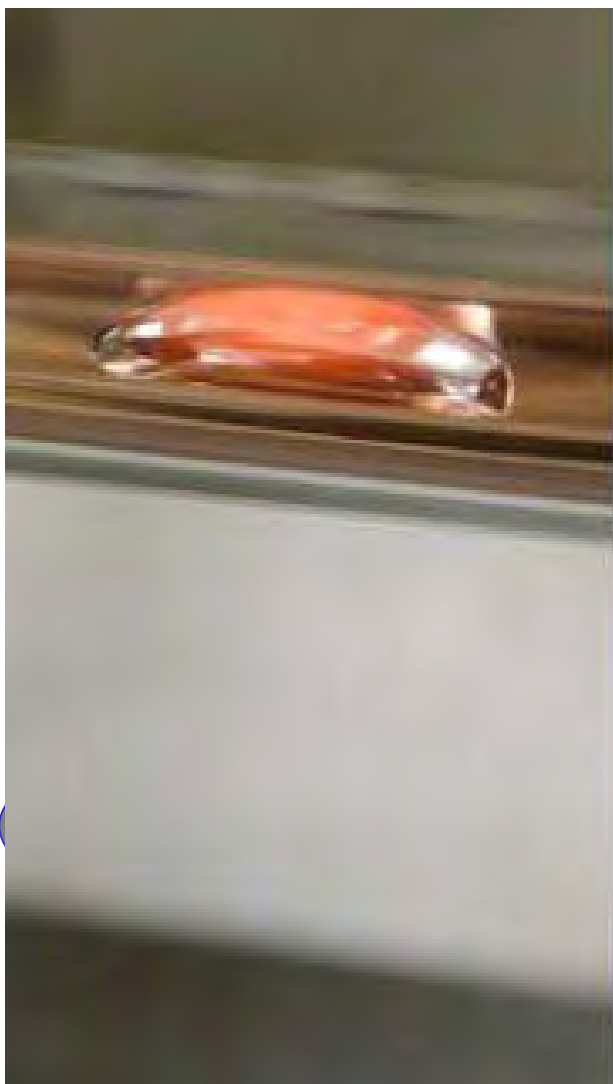
证实金属玻璃可人工合成，发明快冷法

非晶态形成理论取得突破。D. Turnbull, P.W. Anderson, Mott; 形成非晶物理学科

中国金属玻璃年产量达到万吨，世界第二。需求量 >7万吨
变压器损耗降低百分之五十



基本原理 —— 快速冷却，保持液态结构



第二次突破 (1990)

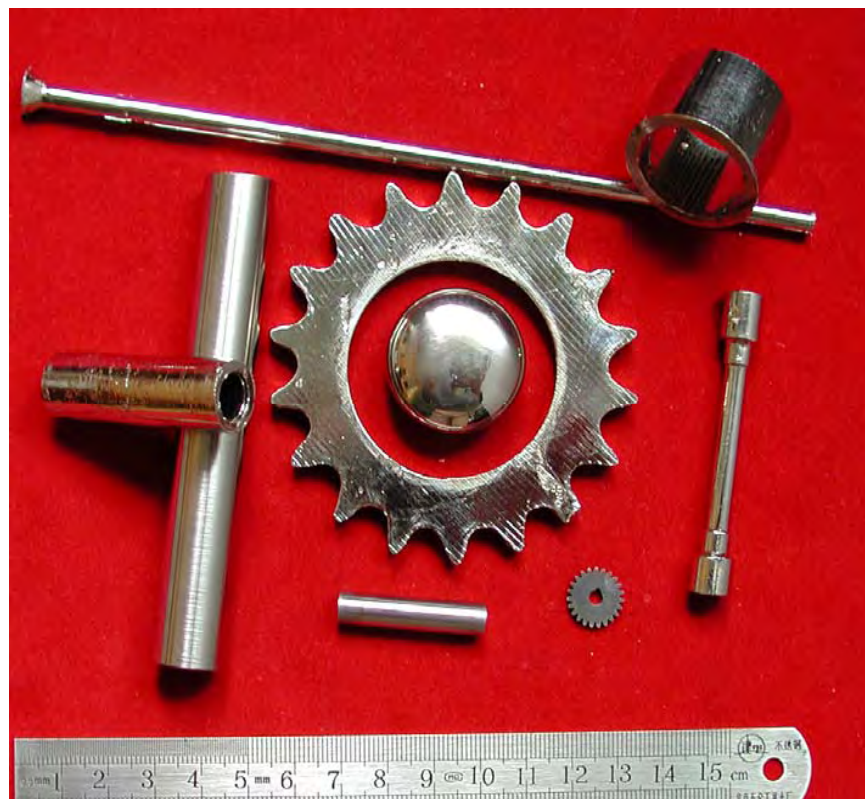
90年代初

制备出大块非晶合金 (0.06 K/s)

95年

应用 (Golf球杆, 穿甲弹等)

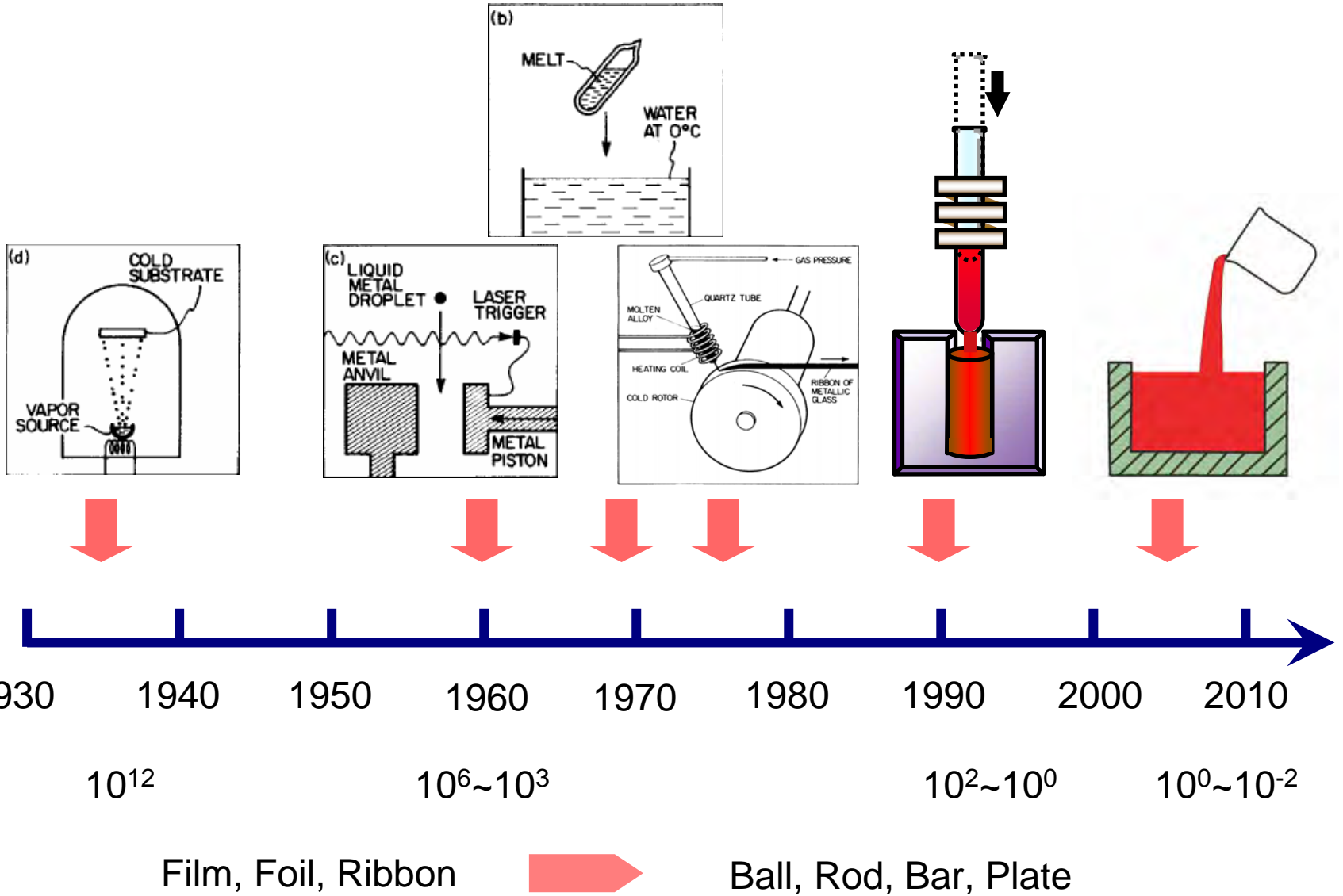
A. Inoue (日本东北大学), W. L. Johnson (Caltech)



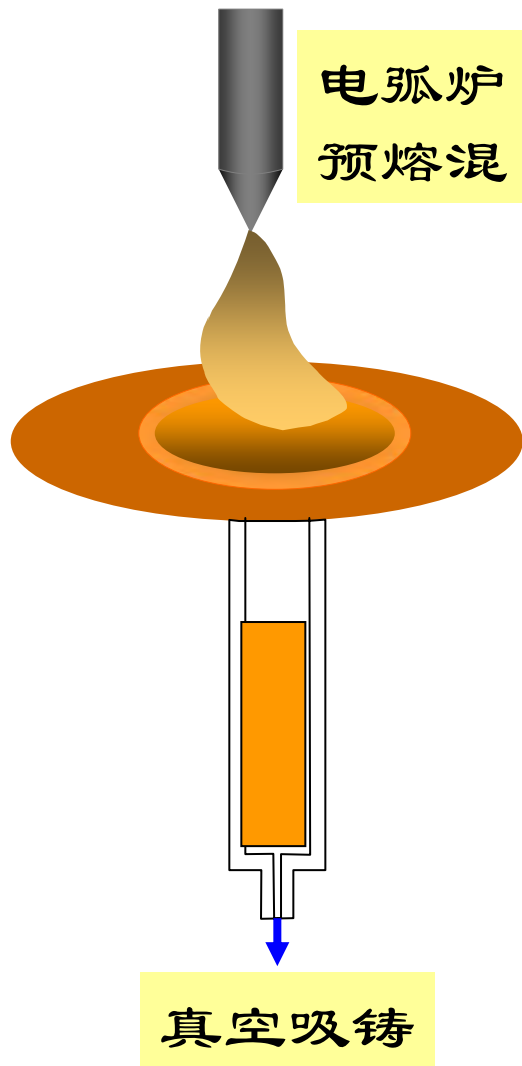
物理所制
备的金属
玻璃

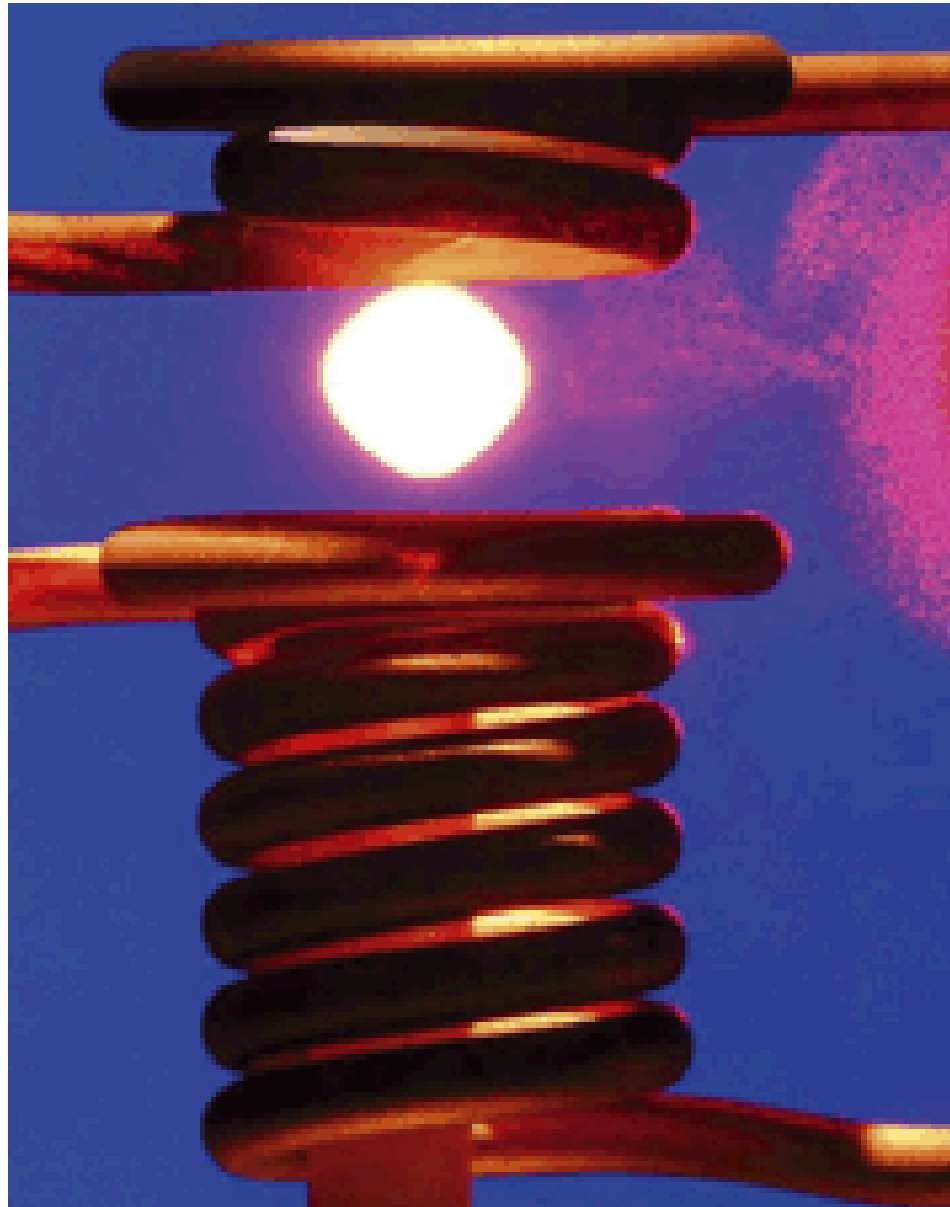


主要制备方法

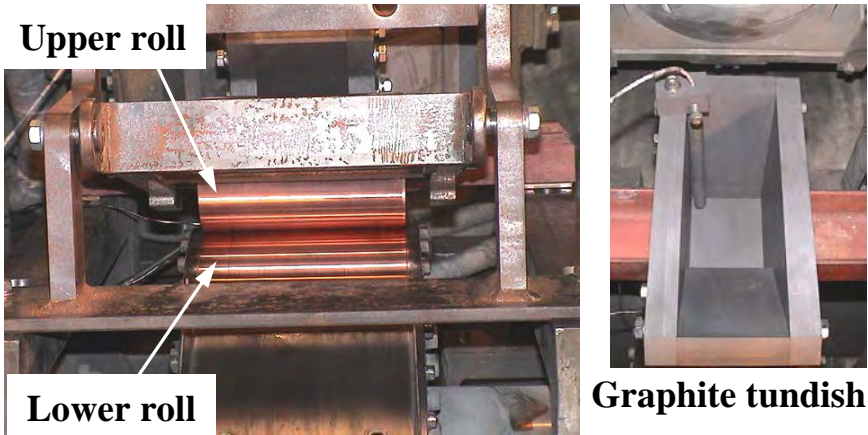


物理所发展的真空吸铸方法

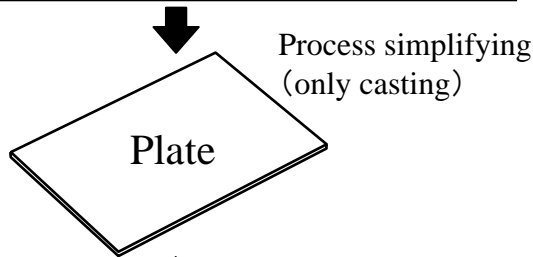




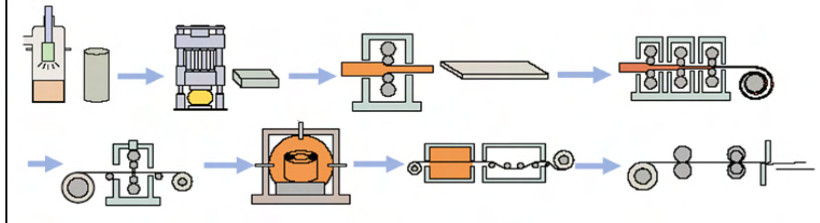
Fabrication process for large scale plates



Newly developed twin-roller quenching



Forming process of Ti-based crystalline alloy



Ti-based BMG large plate with width of 80 mm,
length of 200 mm

80多种体系

- Zr-, Mg-, Ti-, Fe-, Co-, Nd-, Ce- Pd-, Au-, Pt-, Ln系
- 二元 (CuZr) 到 八元 (Fe系)
- 最大尺寸：10 cm直径
- 应用最广泛：Zr系, Fe基
- 形成能力最好：Zr-, Pd-, Ce-BMGs

物理所：约10种新体系

金属玻璃

- 结构像液体
- 兼有固体、金属、玻璃



高强度

$\sigma \propto k / \sqrt{d}$, σ :强度, d : 晶粒尺寸

非晶化是提高强度的重要途径!

提高金属工程材料的强度是材料发展目标之一。降低能耗, 减缓污染

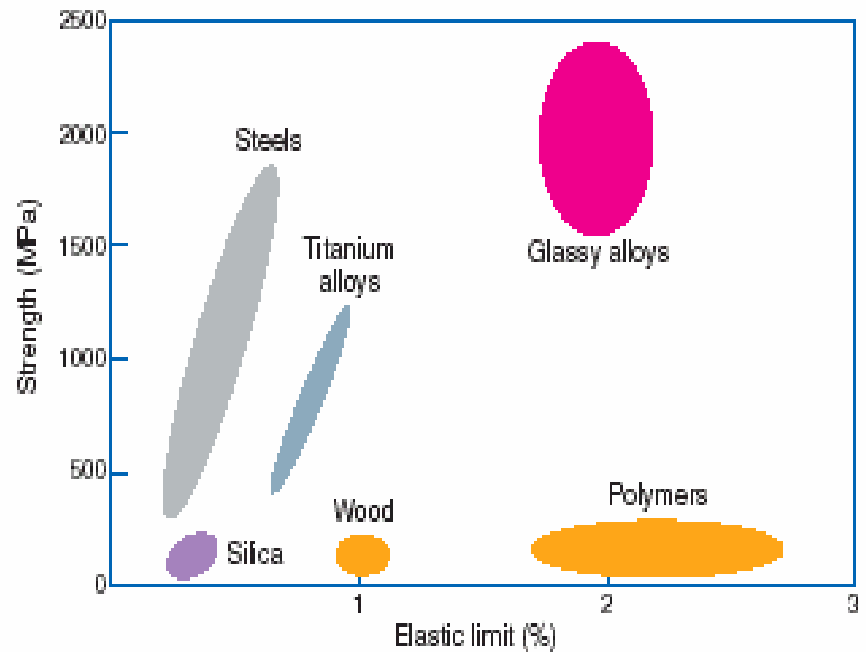
普通钢: 200 MPa,

特种钢: 400 – 700


MPa

BMG: 2000 MPa,

最高: 5500 MPa



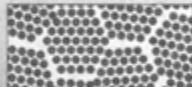
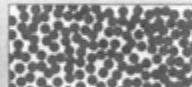
高弹性、低模量

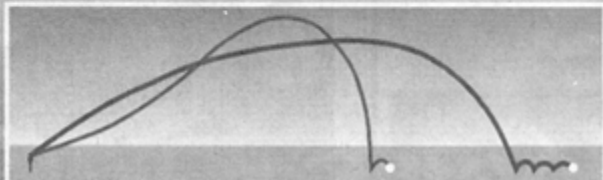


10.5°

LIQUIDMETAL
PURE ENERGY TRANSFER

The unique atomic structure of Liquidmetal alloy makes it stronger than conventional metals, thus allowing Liquidmetal drivers to produce a higher launch angle and a lower backspin rate than titanium drivers with the same loft. This results in a penetrating trajectory with optimum carry and roll for more distance. (As proven in independent tests.)

	
Conventional Metals	LIQUIDMETAL Alloy



Titanium Driver Liquidmetal Driver

Detailed description: This image shows a close-up of a golf driver head. The face is silver and features the 'LIQUIDMETAL' logo and 'PURE ENERGY TRANSFER' text. A white arrow points to the right on the face. The loft is marked as 10.5°. Below the driver head, there is a diagram comparing the atomic structures of 'Conventional Metals' (a regular grid of atoms) and 'LIQUIDMETAL Alloy' (a disordered, liquid-like structure of atoms). To the right of this diagram is a trajectory chart showing two paths: a lower, shorter path for a 'Titanium Driver' and a higher, longer path for a 'Liquidmetal Driver'.



高新技术领域的应用

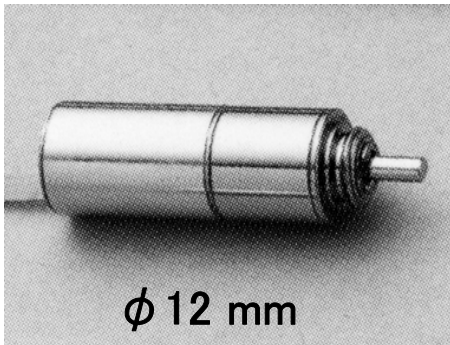
Micromachine  Key device  small & high power motor



µFR (Micro • flying • robot)
(SEIKO EPSON)

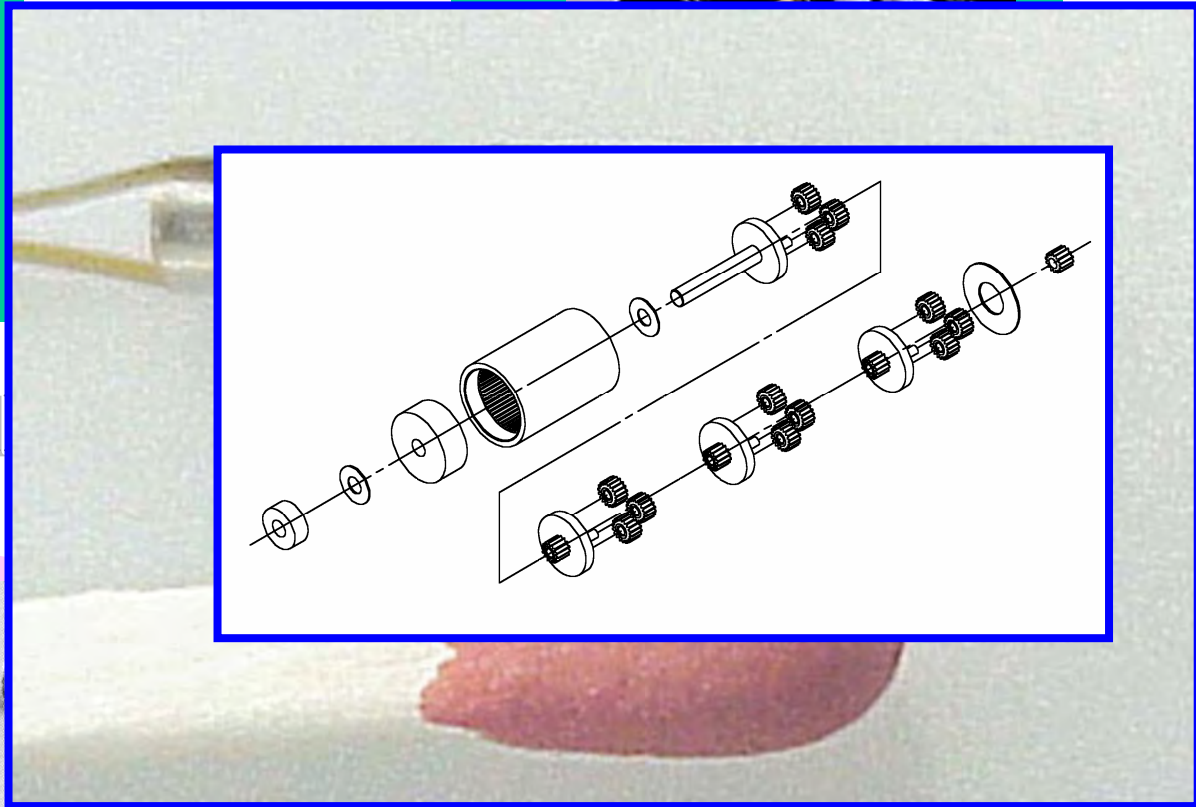
Small

1980



φ 12 mm

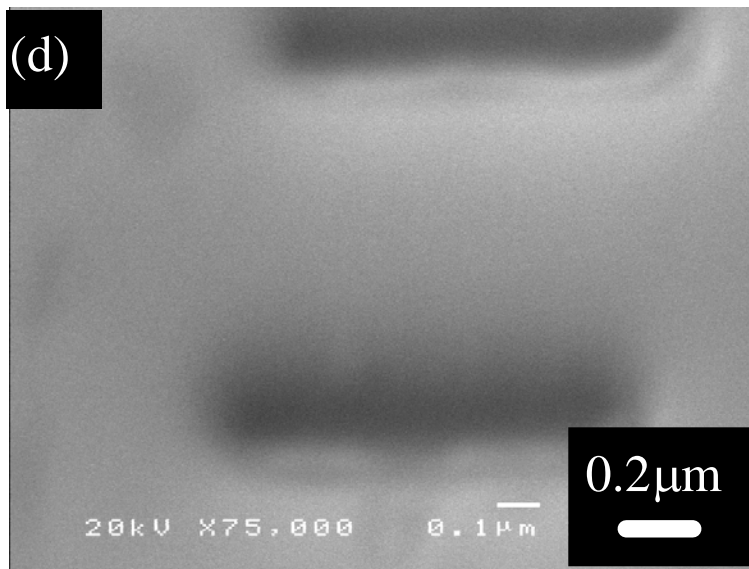
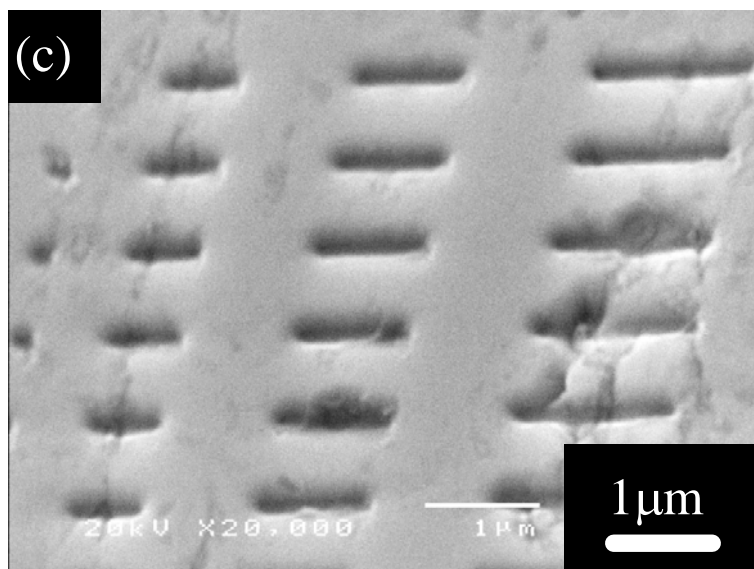
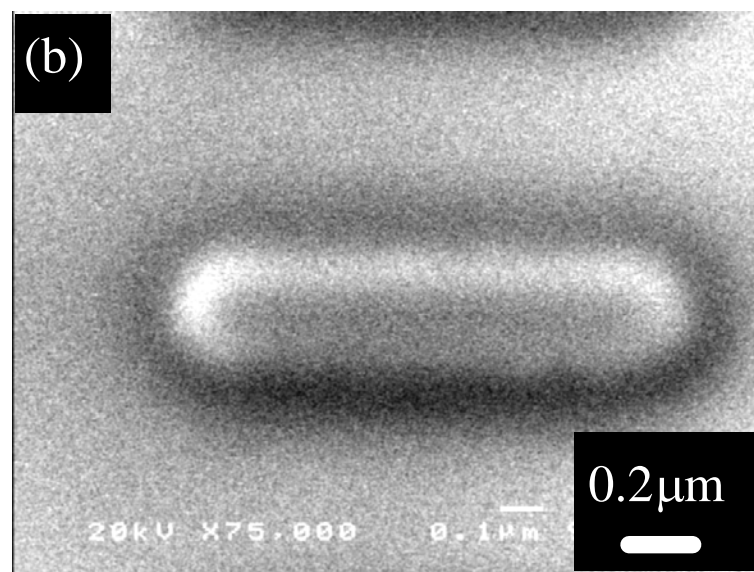
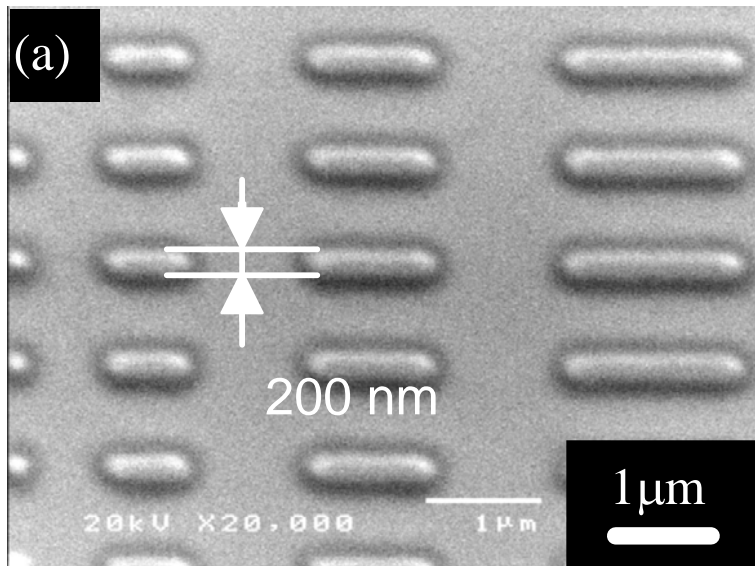
- Camera
- Handpiece



- Small camera
- Endoscope
- Measurement systems
- Catheter

• Surface flatness

Miniaturizing trend of micro-gear motor



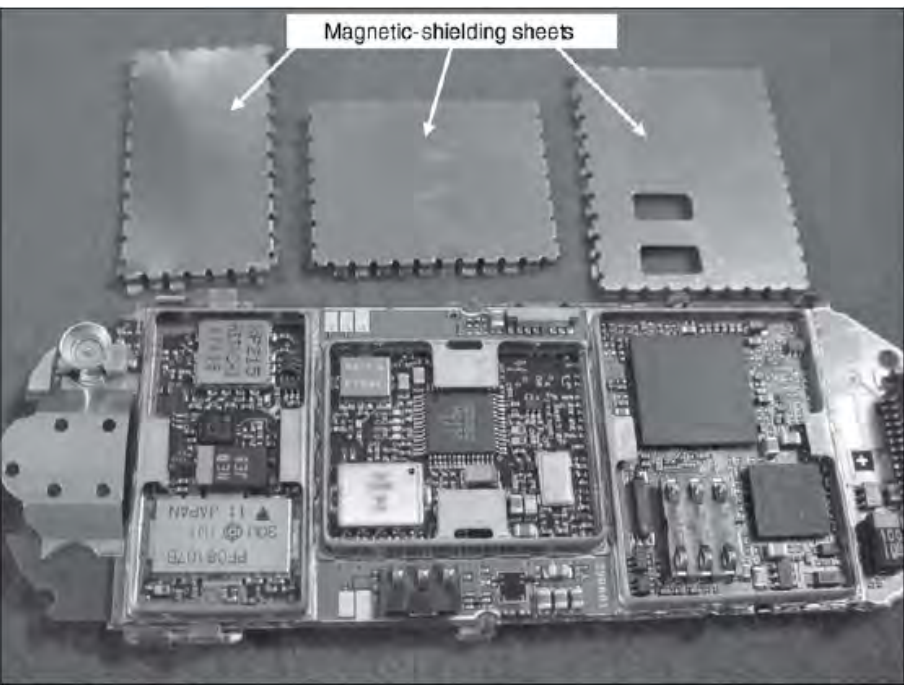
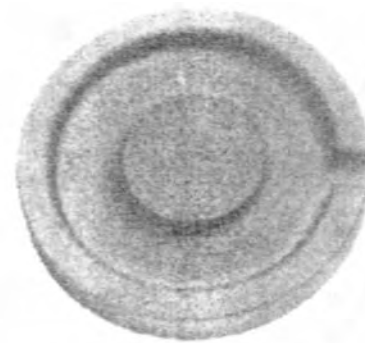
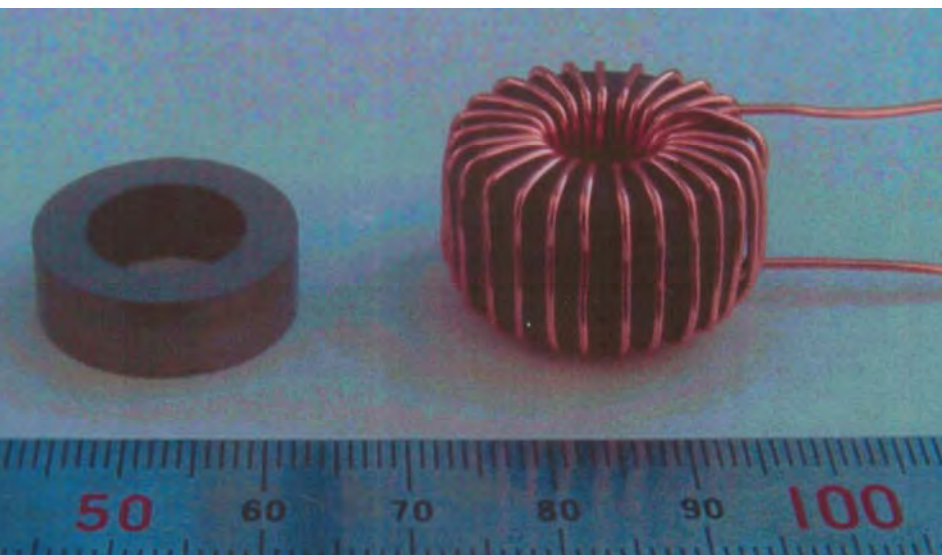


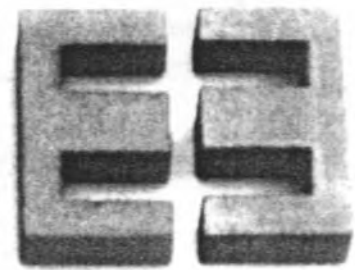
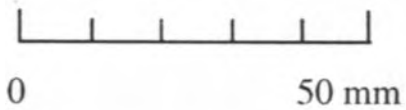
Figure 2. Bulk metallic glass magnetic-shielding sheets for laptop PCs.



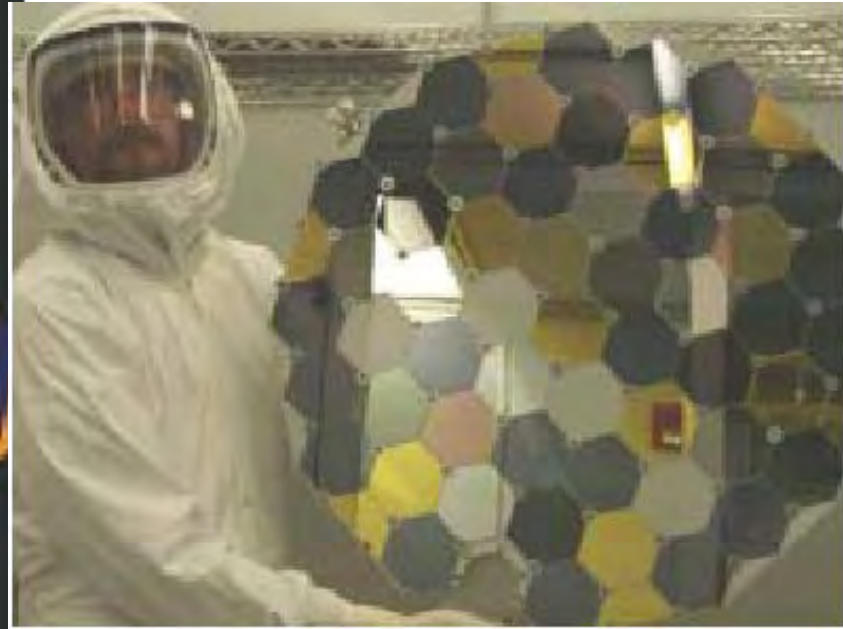
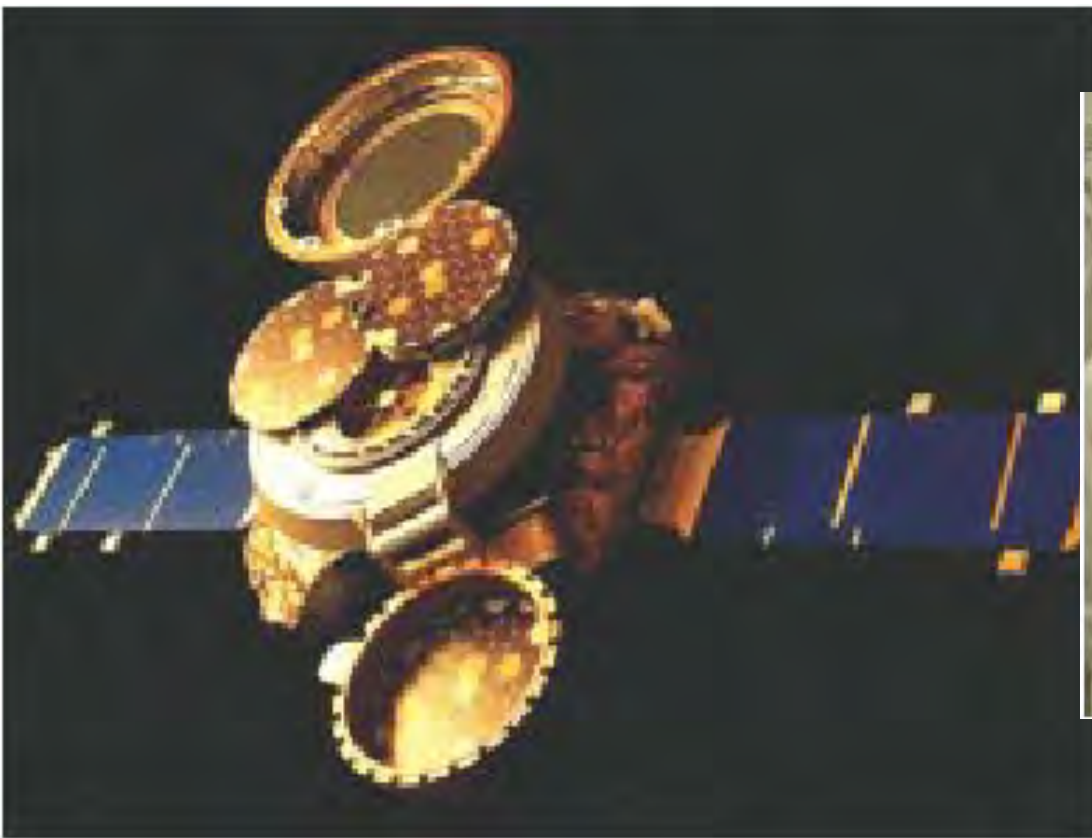
Pot-shape core



Toroidal core



E-shape cores



创世纪计划：捕捉太阳风， 获得了0.1克太阳物质！

Science, 314, 1133(2006)

二、科学问题

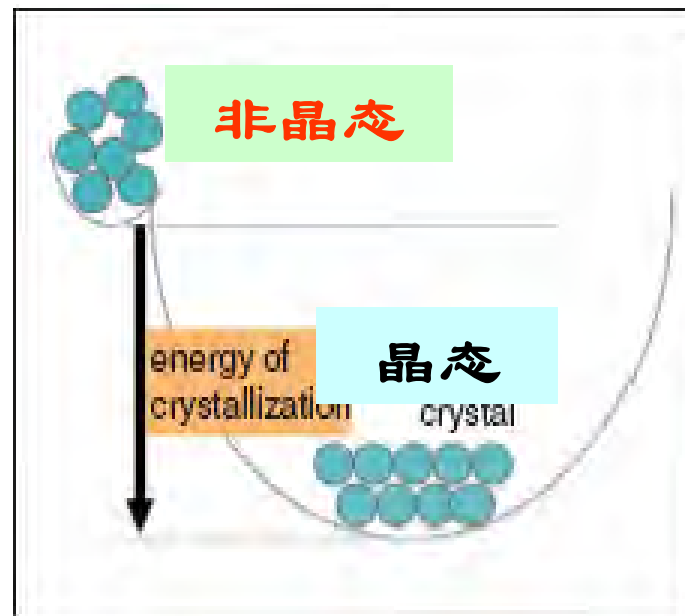
核心科学问题

凝聚成非晶态的物理机制：

- 凝聚成能量上是亚稳态的物理机制和条件？
- 非晶的弛豫机制，控制和稳定性？
- 预言在什麼系统和成分制备出性能可控非晶材料



缺乏探索非晶材料的有效判据



非晶的合成和堆沙子很类似

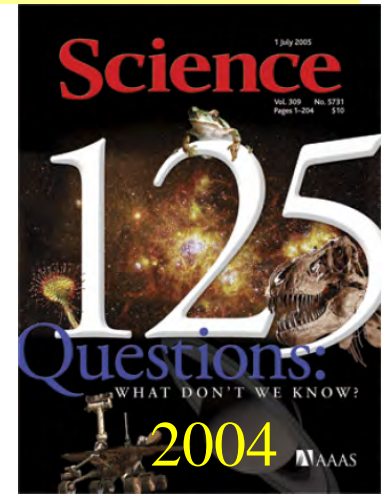
凝聚成非晶态的物理机制

- ◆ 液体—非晶转变是自然界中一大类重要的转变；如地质构造、地貌的形成，生命过程、生命保存，食物速冻保鲜，生物物质的凝固现象等
- ◆ 凝聚态物理的范式不适用
原子、电子结构变化很小 (V , S , H 变化小)
物理性质发生巨大变化
 T_g 是物质的重要特征
- ◆ 无序、不稳定、随机性、复杂性、不可逆是非晶物质的基本要素
- ◆ 自组织， 无序， 复杂性， 时间起重要作用→ 新的物质观
- ◆ 非晶研究促进新概念、理论、思想产生

非晶形成机理是本领域最核心的科学问题

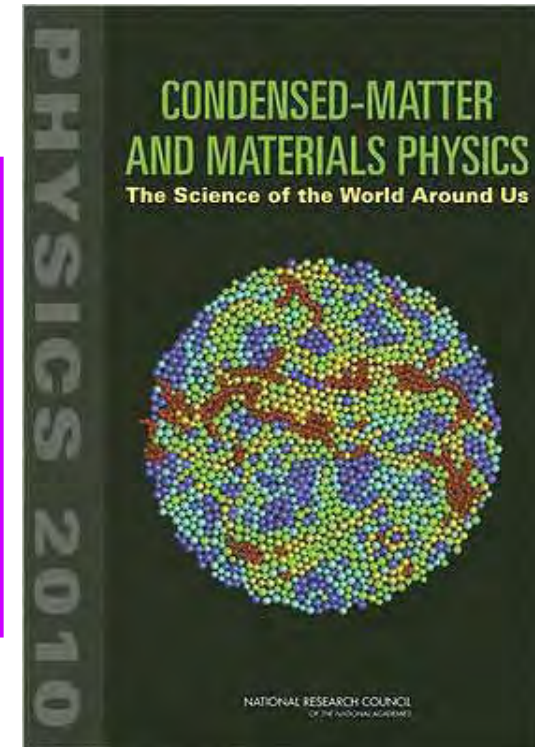
开展玻璃材料研究的科学意义：

2005年7月《Science》玻璃形成机理和玻璃的本质被列入125个主要科学问题之一



P.W. Anderson

玻璃形成机理和玻璃的本质是21世纪凝聚态物理最重要的问题之一 Science, 267 (1995)1615



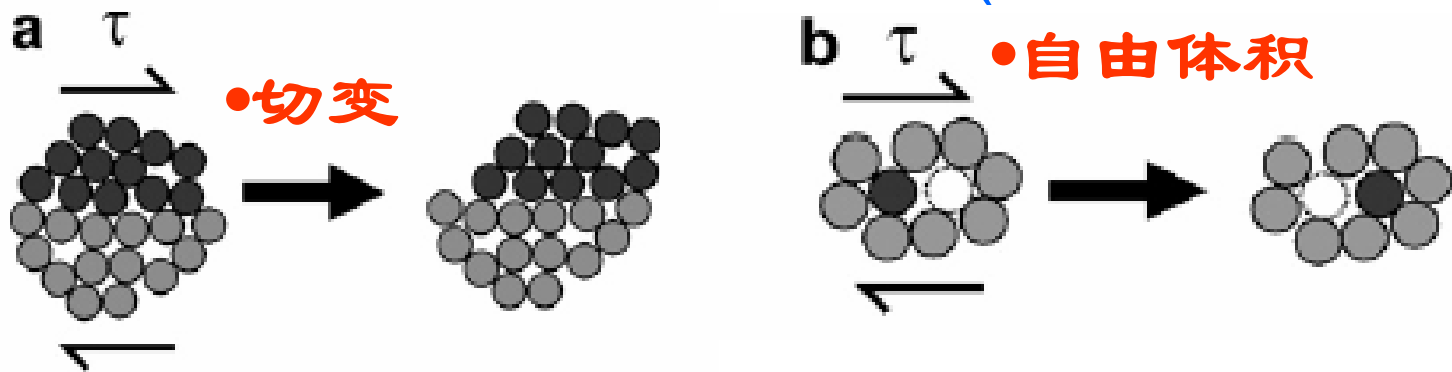
非晶塑性机理及脆性难题

两大问题：

1、室温脆性——应用的最大难题

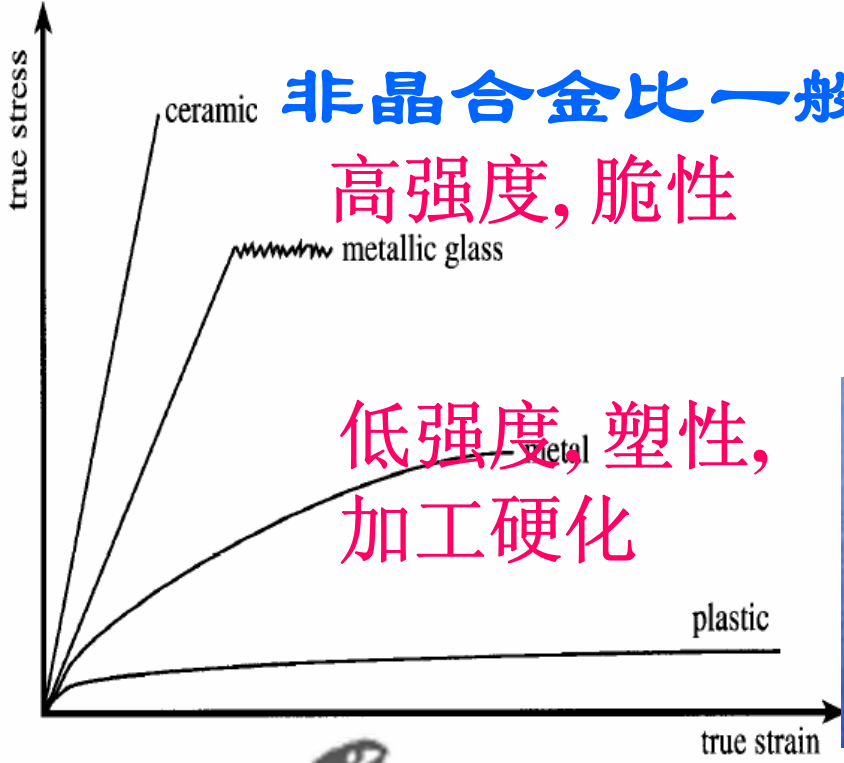
2、非晶形变、断裂机理

现有非晶合金形变模型 (上世纪70年代提出)



不能解释塑性宏观形变；不能指导塑性非晶探索

室温脆性——非晶应用的重大难题



非晶合金比一般合金强度高2-3倍

高强度, 脆性

低强度, 塑性, 加工硬化



塑性 < 2%



大力神Achilles的脚后跟——金属玻璃脆性

形变、断裂机理

1934年提出位错模型成功解释金属塑性，发展了固体缺陷理论

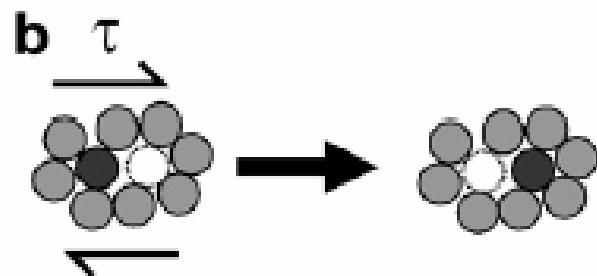
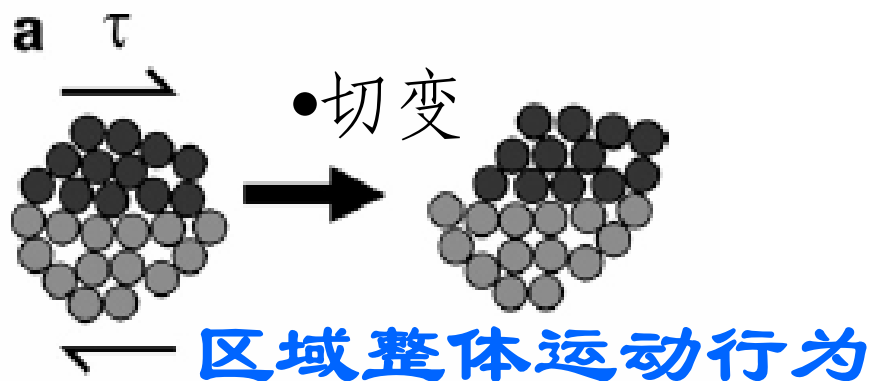
晶态材料

较完善的形变、断裂理论

现有非晶合金形变模型

非晶材料

对形变机理认识不够，没有形变、断裂理论



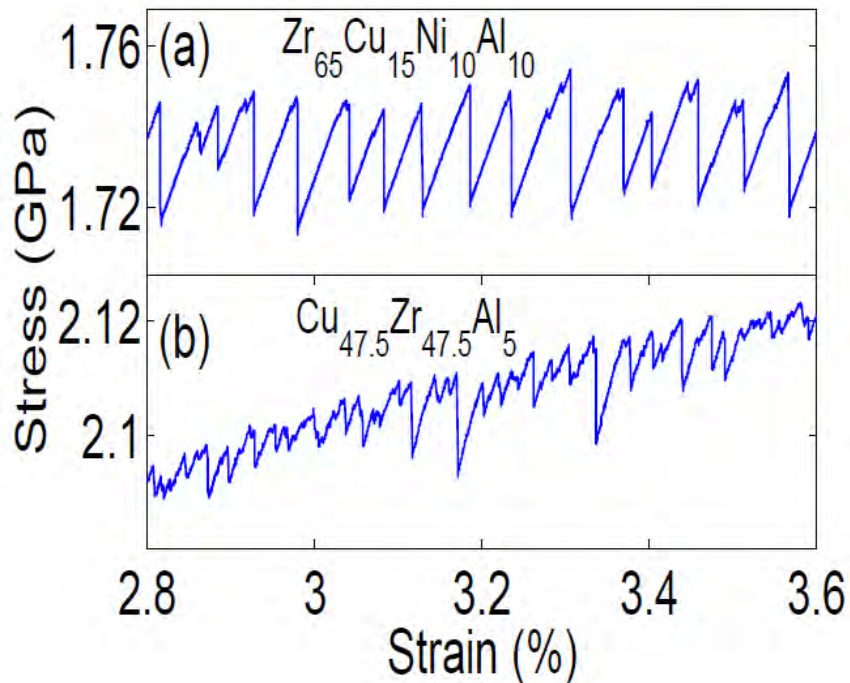
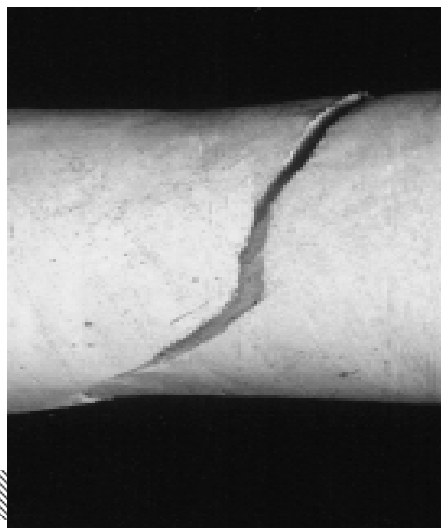
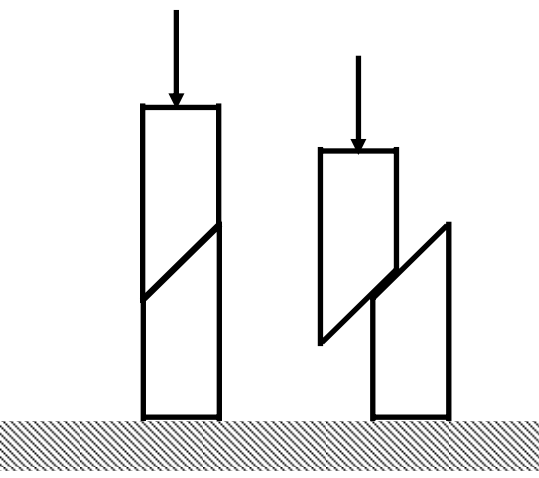
原子运动行为



金属玻璃断裂研究

A. A. Griffith 1920年发表“固体的断裂和流变”，采用能量平衡原理解释断裂

被列为材料和工程领域历史上最伟大的50事件之一



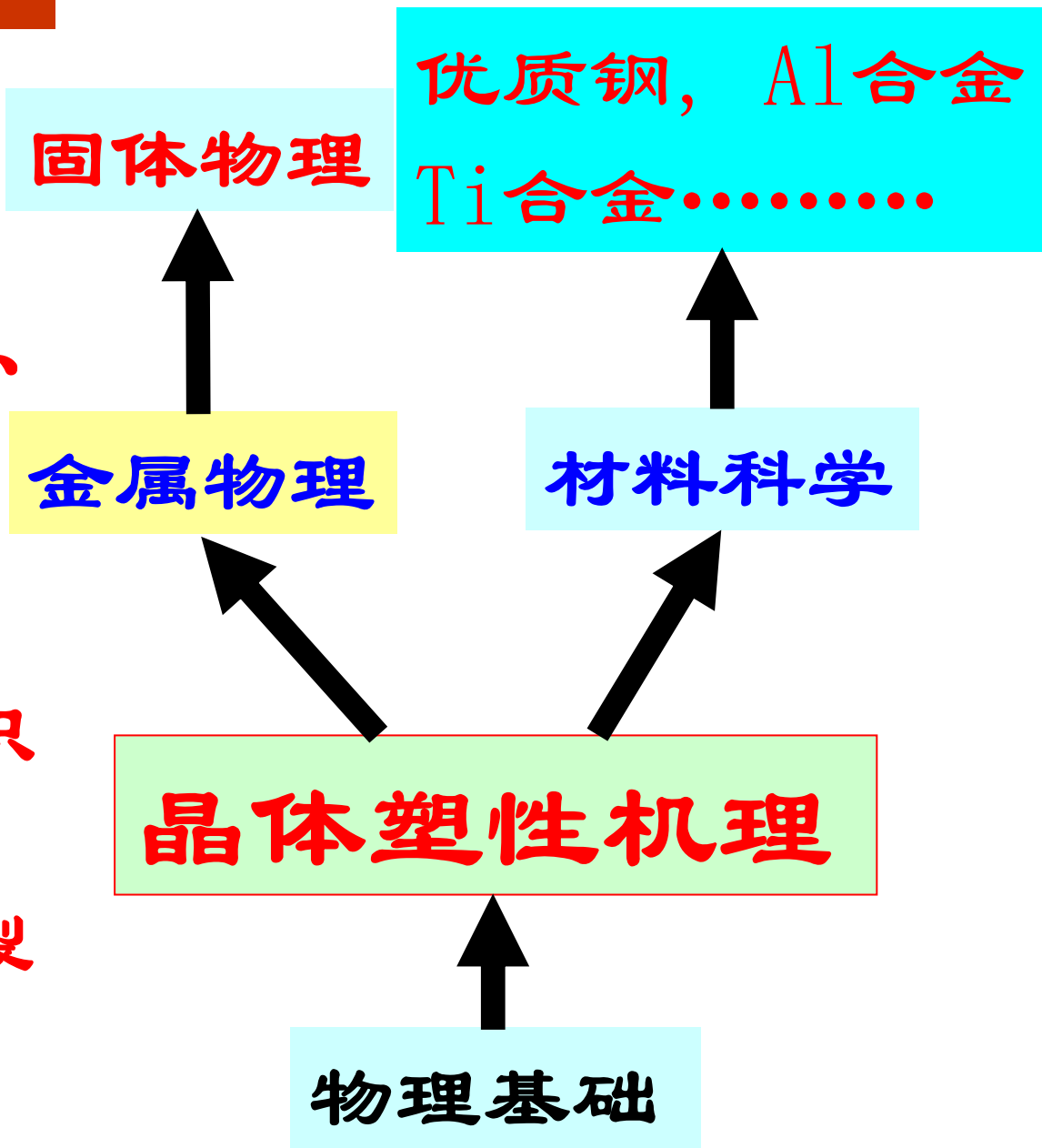
非晶的形变机理

晶态材料：

- 较完善的形变、断裂理论

非晶材料：

- 对形变机理认识不够；
- 没有形变、断裂理论。



原子无
序密堆



原子团无
序密堆

问题：非晶结构，
结构和性能关系

短程序

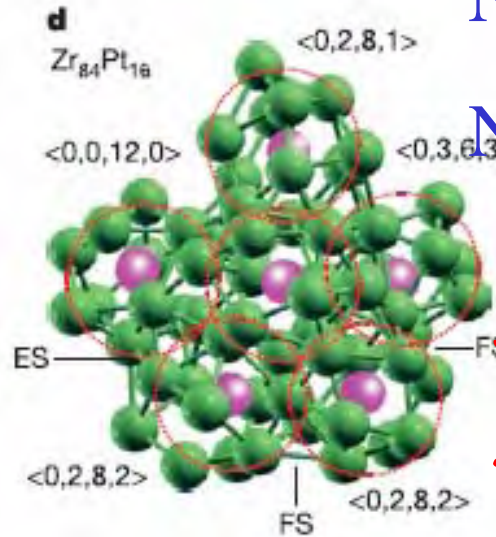
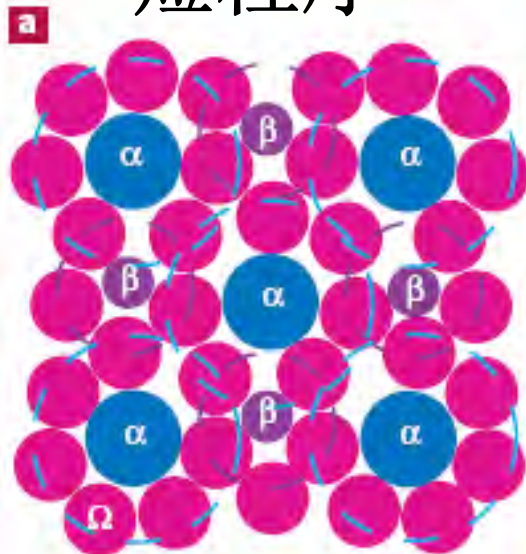


中程序



短程序

Nature Mat 3, 697 (2004)



Nature, 439, 419 (2006)

微观结构观测、描
述的困难是很多难
题的主要症结

三、研究进展

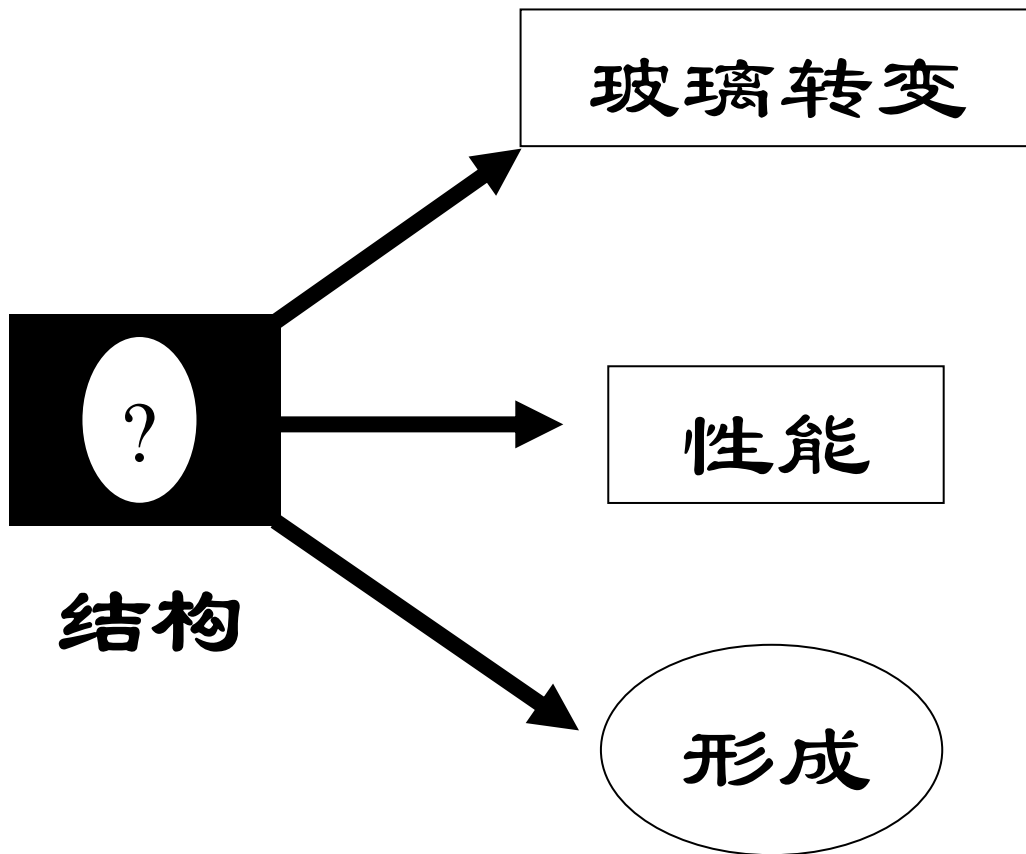
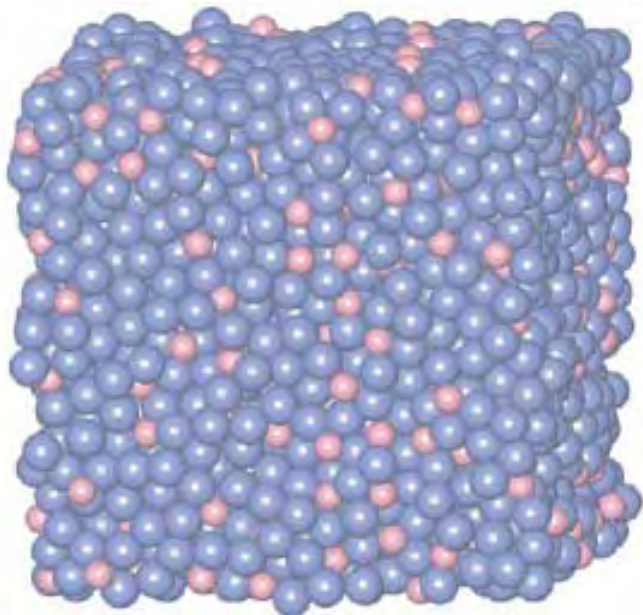
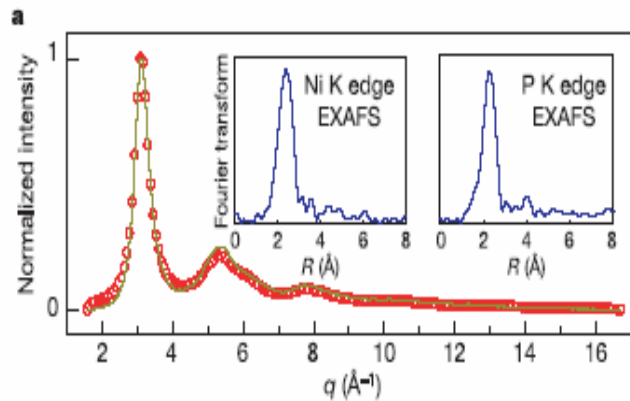
- 非晶合金形成机理的认识
- 非晶新材料的研制
- 非晶脆性和形变机理
- 非晶研究与其它领域的联系

1、非晶形成机理的认识—模量 模型和判据的建立

问题的主要症结

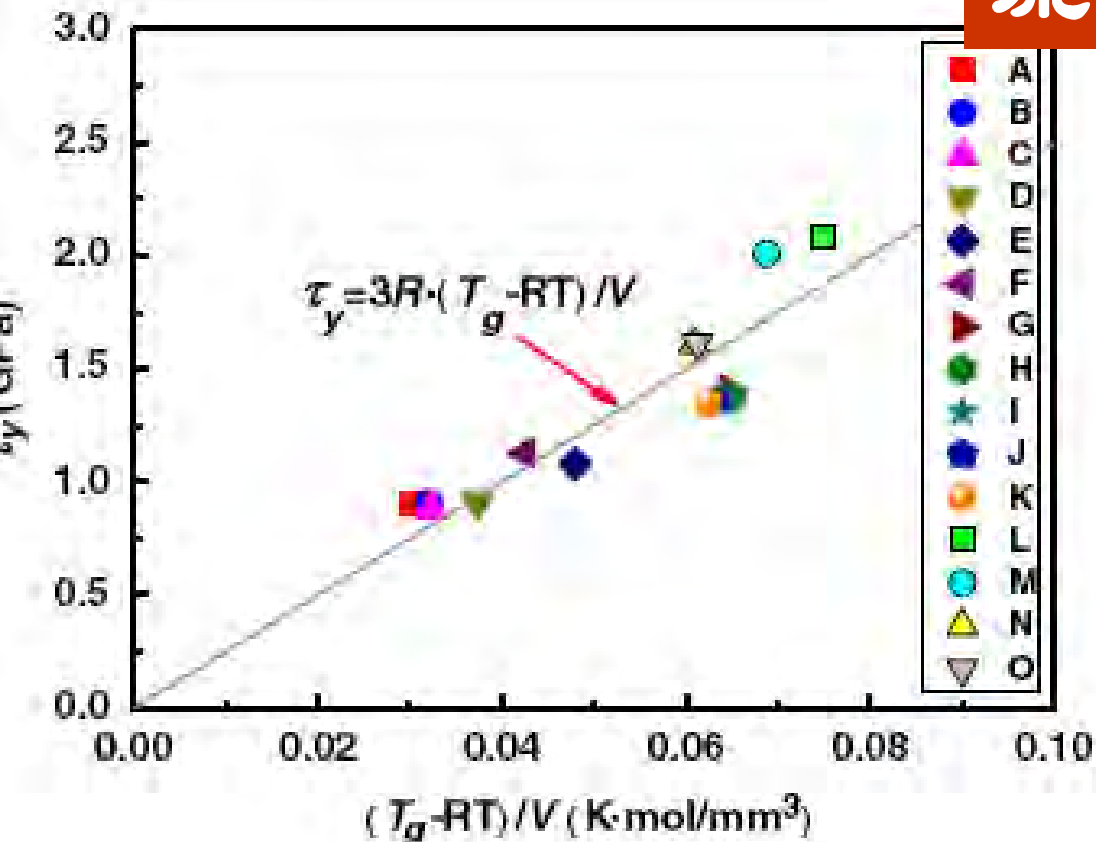
形变机理的建立取决于微观结构

微观结构观测、描述的困难



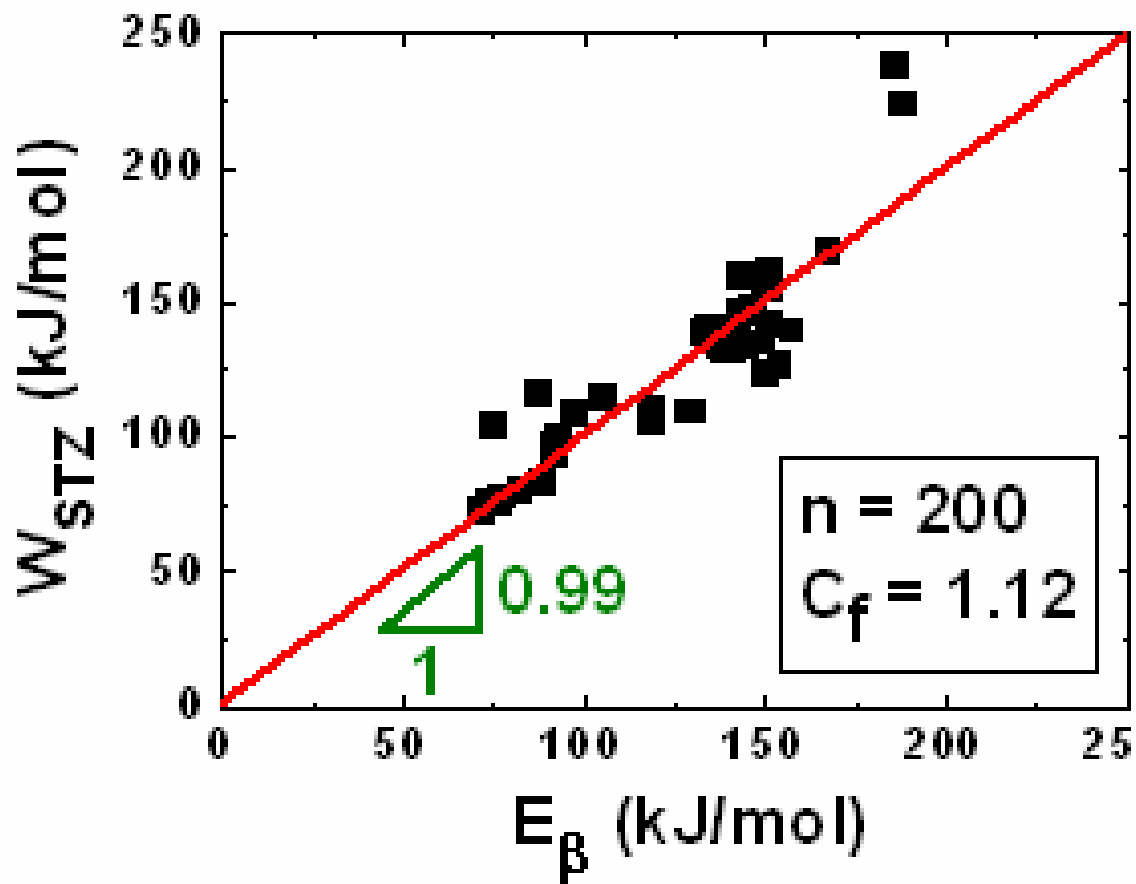
非晶的形变屈服与流动的关系

屈服对应于玻璃转变

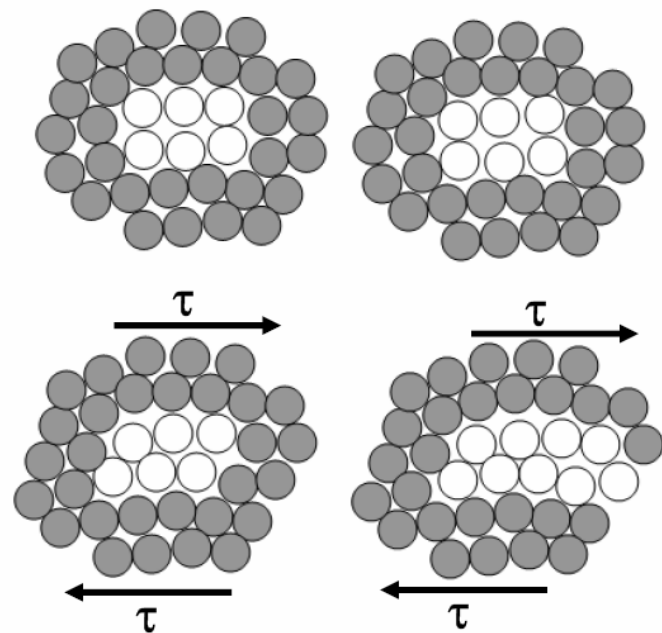


PRL 103, 065504 (2009)

宏观上，屈服和流变具有类似性，形变可看作局域的流动！



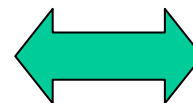
$$W_{STZ} \approx E_{\beta}$$



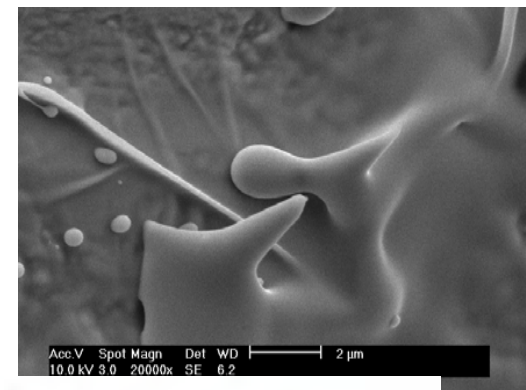
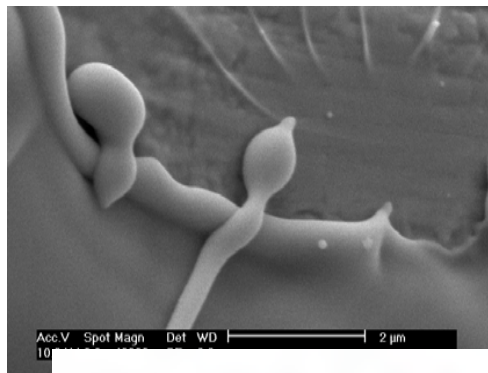
流动基本单元和
 形变基本单元密切相关

非晶合金中的“流变”

非晶形成：流动的冻结过程

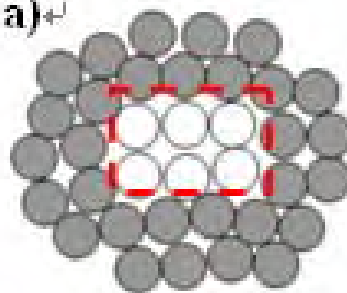


非晶的形变：力作用下，玻璃中的局域流动

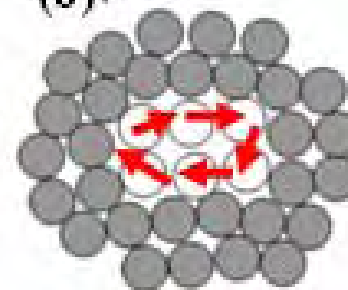


非晶中的弛豫：从高能态向低能态的过渡

(a)



(b)



Free volume model

$$\eta = \eta_0 \exp[C(T)/k_B T]$$

VFT 方程

$$\eta = A \exp[B / (T - T_0)]$$

Adam-Gibbs构型熵

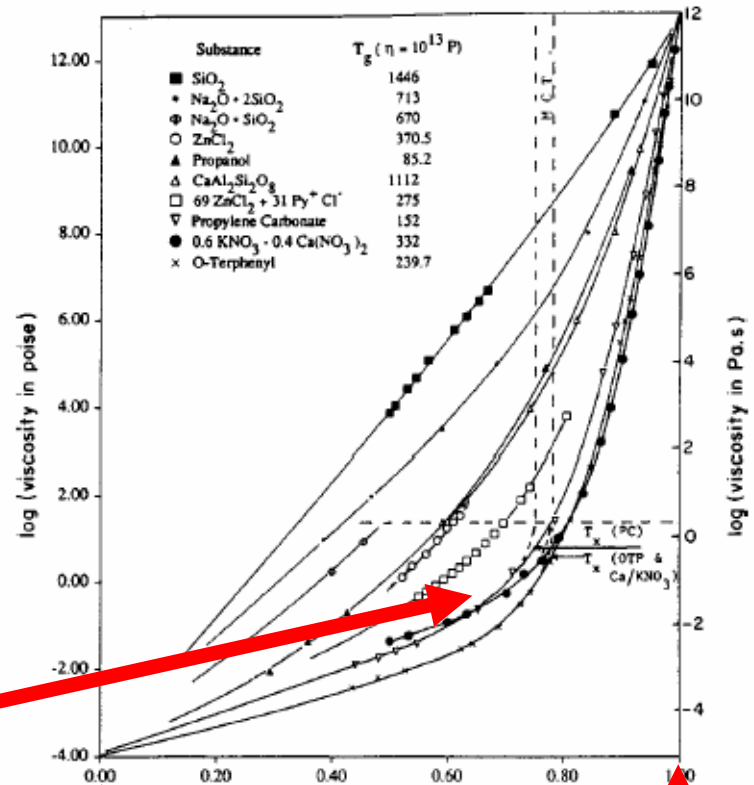
$$\eta = \eta_0 \exp[C / TS_{conf}(T)]$$

序参量模型

Mode coupling theory

$$T = T_g, \eta = 10^{13}$$

$$T = \infty, \eta = 10^{-4}$$



$$\eta = \eta_0 \exp[\Delta E(T)/k_B T]$$

$T = \infty$ ↑ 过冷液体 ↑ T_g

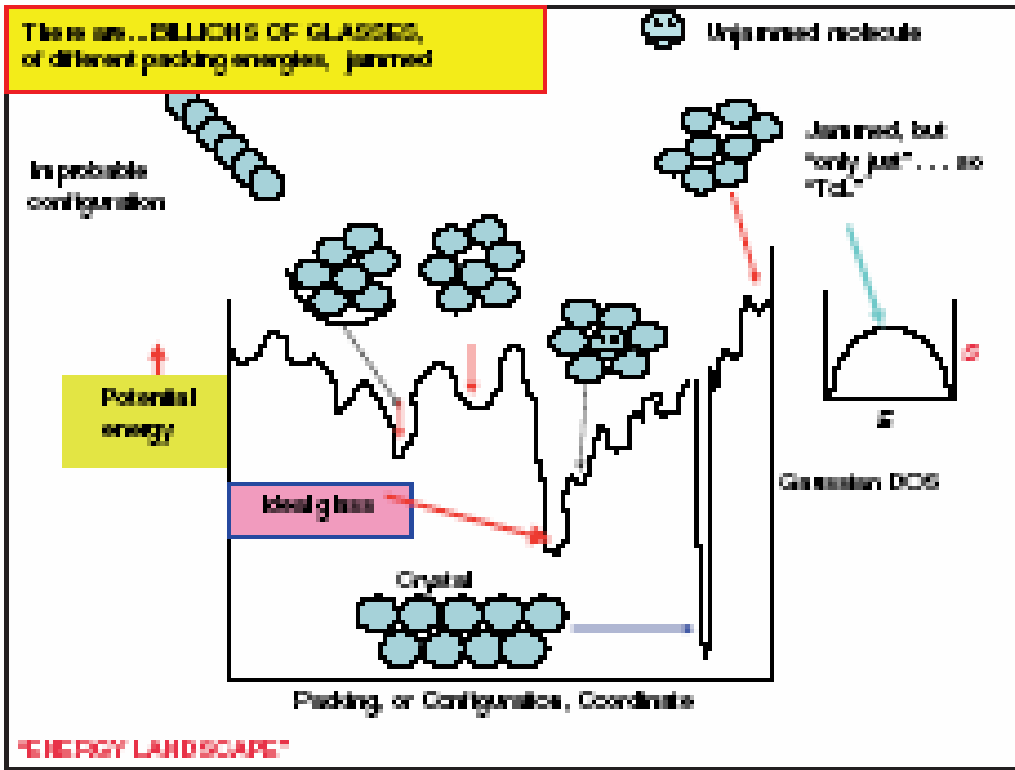
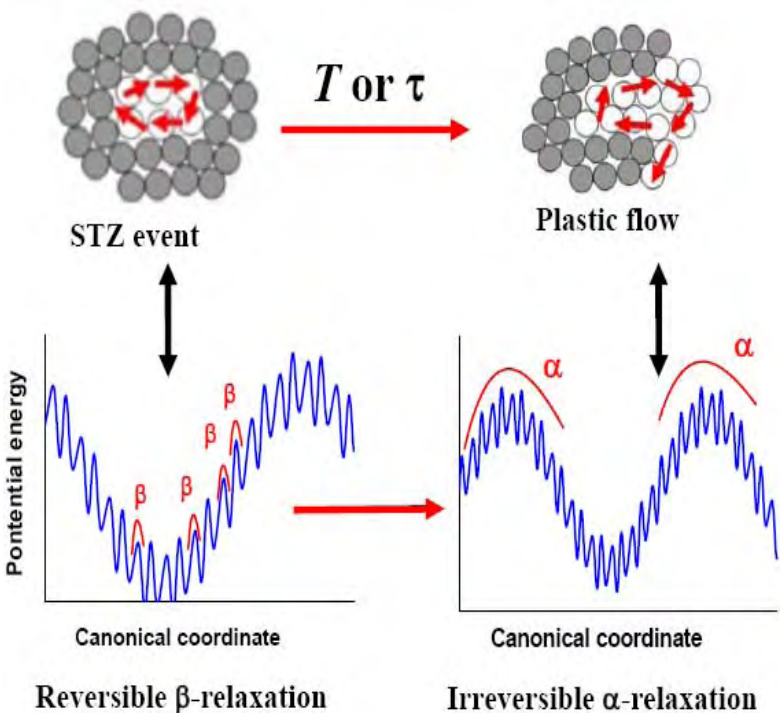
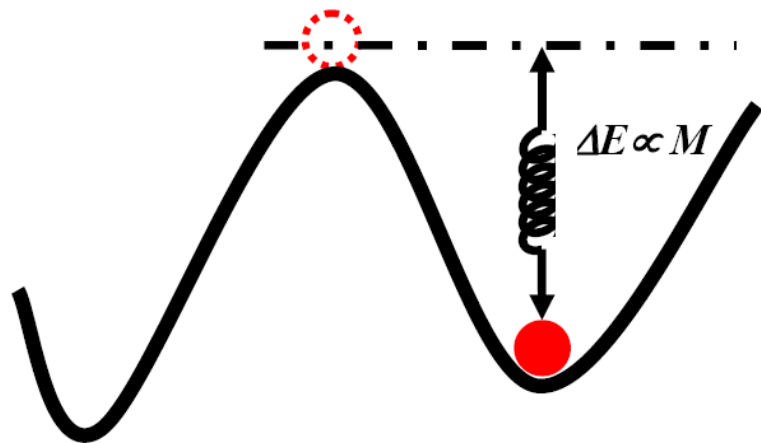
~10K 温度, 10^{13} 的粘度变化

归结为流动问题：

$$\eta = \eta_0 \exp[\Delta E(T)/k_B T]$$

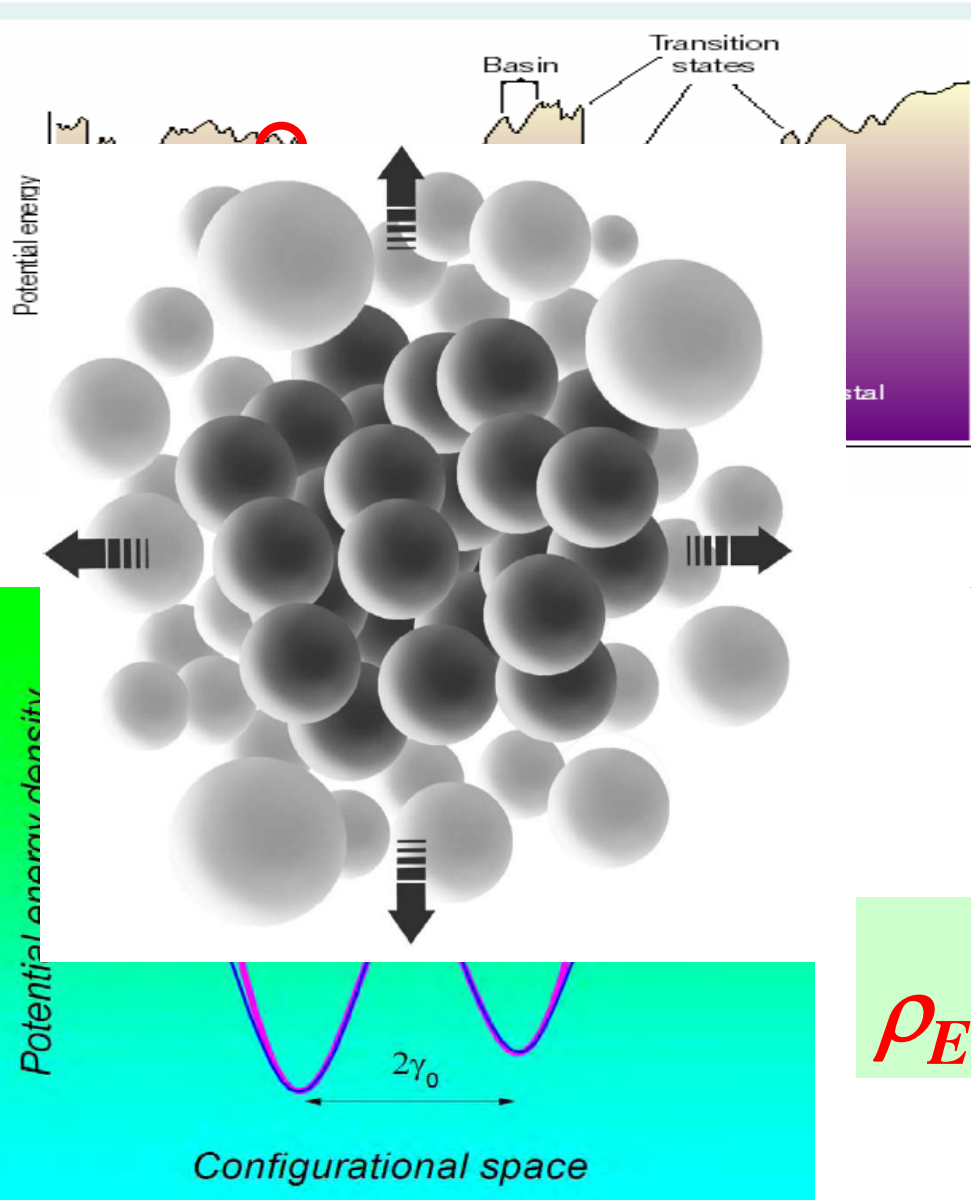
非晶的流变是从一个非晶构形态到另一个构形态的跃迁

非晶的‘流变’与能量形貌图的对应



理论分析

激活能密度表达式



$$\rho_E = \frac{1}{2} M \gamma^2$$

M —弹性模量, γ 为—应变

$$\rho_E = \frac{1}{2} M \gamma_0^2 = \frac{1}{2} \frac{k_B T}{\langle \gamma^2 \rangle} \gamma_0^2 \propto \frac{k_B T}{\langle \gamma^2 \rangle}$$

$$\rho_E = (1-\alpha)G + \alpha K$$

$$\rho_E = \Delta E / V_m = (10G + K) / 11$$

PRB 81, 220201 (2011)

从弹性模量角度研究非晶形成机理等问题

- 非晶各向同性, 其弹性模量很容易实验测量
- 弹性模量物理意义清楚, 和原子间键, 势能相关
- 模量可敏感反映结构的变化

$$G_{\infty} = \rho k_B T + \frac{2\pi\rho^2}{15} \int_0^{\infty} \frac{d}{dr} \left[r^4 \frac{dU}{dr} \right] g(r) dr \quad K_{\infty} = \frac{5}{3} G - \frac{4\pi\rho}{12} \int_0^{\infty} \left[r^3 U'(r) \right] g(r) dr$$

模量模型:

非晶的形成、形变、弛豫都可用流动来描述

实验和理论证明: 流动的激活能和模量成线性关系

模量是控制非晶形成、稳定性和性能的关键参量

$$\eta = \eta_0 \exp[\Delta E(T)/k_B T]$$

$$\Delta E(T) \propto \text{模量}$$

- 简化复杂问题
- 与实验易测量模量关联

代表文章被引用1000多次

获2010年国家自然科学二等奖

Maxwell 是第一个把弹性模量和流动关联的人：

$$\tau_R = \eta/G_\infty \quad (1776\text{提出})$$

自然科学：比拟流体流动进行研究：热流， 电流， 磁流体， 光学比拟流体波动的“波动说”，……

万物皆流！ —— 古希腊哲语



在系统研究300 多种不同非晶合金的基础上， 建立非晶材料中弹性模量和性能、形成能力之间的关联

◆ ZrBe-, Zr-基非晶

◆ La-, Ce-, Pr-, Nd-, Sm-, Gd-, Tb-, Dy-, Ho-, Er-基非晶

◆ Cu-, Fe-, Co-, Ni-, Ti-基非晶;

◆ Pd-, Au-, Pt-基非晶;

◆ Ca-, Mg-基非晶

◆ 二元非晶 (CuZr, CuHf, NiNb, PdSi)

◆ 非晶条带

◆ 氧化物玻璃

◆ 其它玻璃

50 多种非晶合金

300多种成分

随压力、温度的变化

具有不同的性能

● 强度: 0.2 GPa ~ 5.4 GPa

● 韧性和脆性非晶

● E : 20 GPa – 300 GPa

● $T_g \sim 60 - 900$ C

● 强和弱非晶合金

实验验证

$$\eta = \eta_0 \exp[\Delta E(T)/k_B T]$$

$$\Delta E(T)/k_B T \Big|_{T_g} = \text{常数}$$

$$\frac{\rho_E V_m}{RT_g} = \frac{(0.91G + 0.09K) V_m}{RT_g} \equiv \text{constant}$$

统计发现46种不同块体金属玻璃

体系的实验数据值

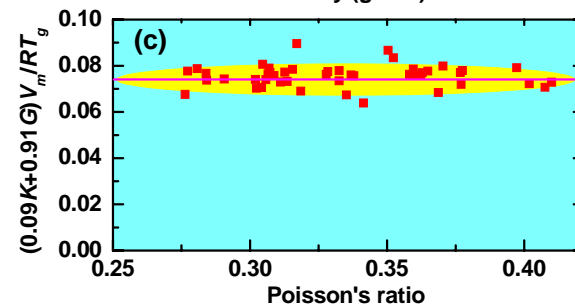
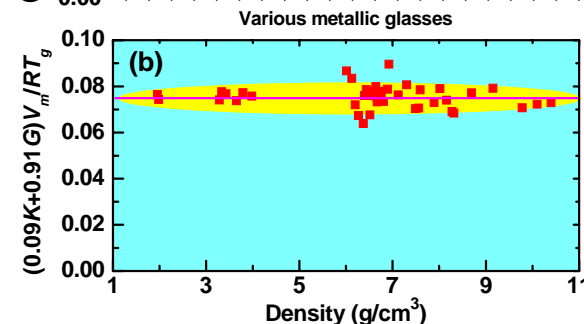
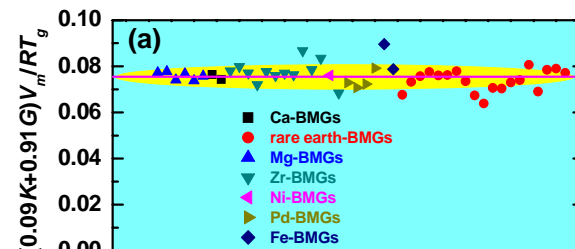
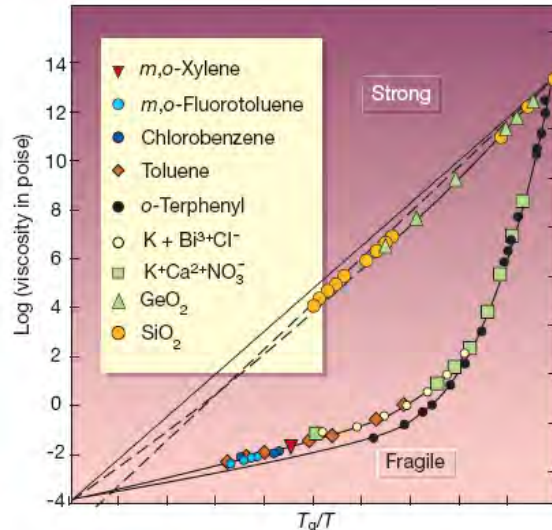
$(0.91G+0.09K) V_m/RT_g$ 与材料体

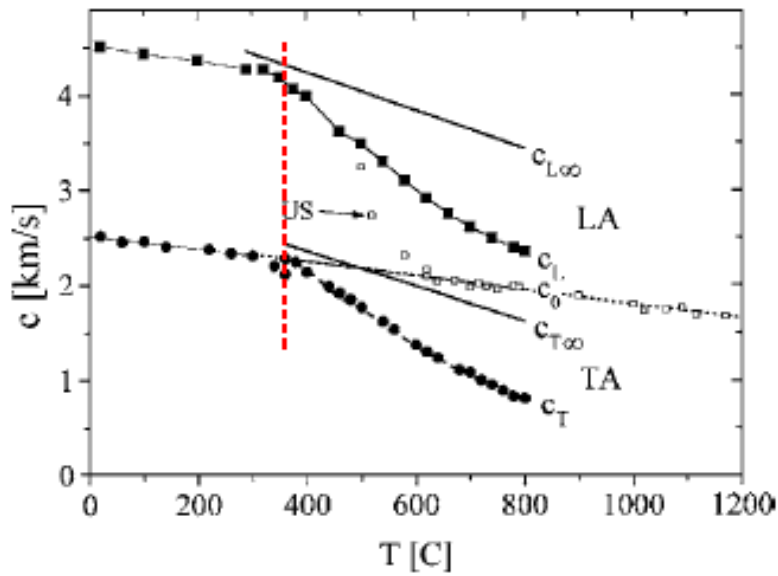
系及其性质没有明显的依赖关

系，可以用常数0.075拟合地很好

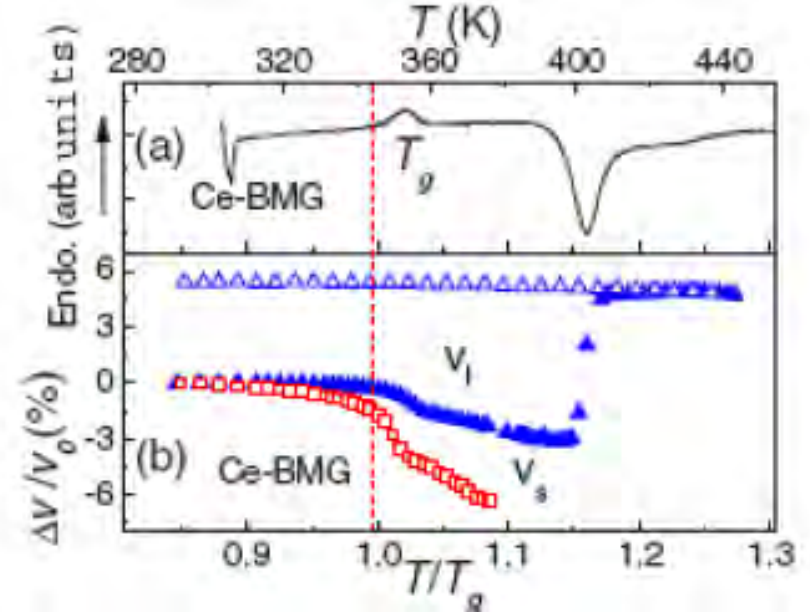
当G和K的贡献是 $\approx 10:1$, 即

$$\rho_E = (10G+K)V_m/11$$





Rev. Mod. Phys. **78**, 953, (2006).



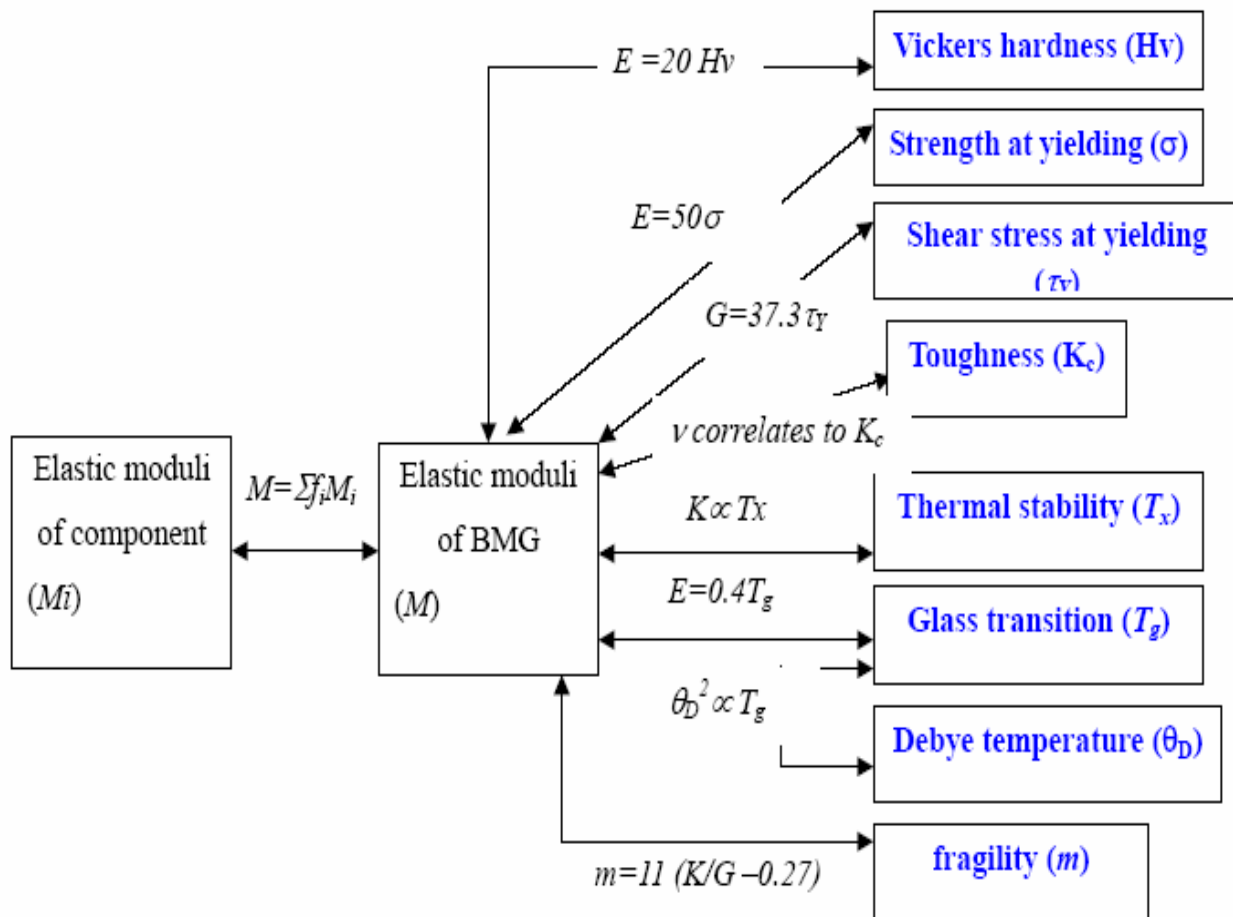
Phys. Rev. B **76**, 012201 (2007).

$$\frac{\Delta V_S}{V_S} : \frac{\Delta V_L}{V_L} \approx 2 : 1$$

$$\rho_E = (10G+K)/11.$$

$$\left. \begin{aligned} \rho V_S^2 &= G \\ \rho V_L^2 - \frac{4}{3} \rho V_S^2 &= K \end{aligned} \right\} \begin{aligned} &\frac{\Delta V_S}{V_S} : \frac{\Delta V_L}{V_L} \approx 2 : 1 \\ &V_S/V_L \approx 0.5, \nu \approx 0.333 \end{aligned} \longrightarrow \frac{\Delta G}{G} : \frac{\Delta K}{K} \approx 5 : 1$$

在系统研究300 多种不同非晶合金的基础上， 证明
模量和玻璃流动及特性和性能、 形成能力之间的关联



发现各种关联

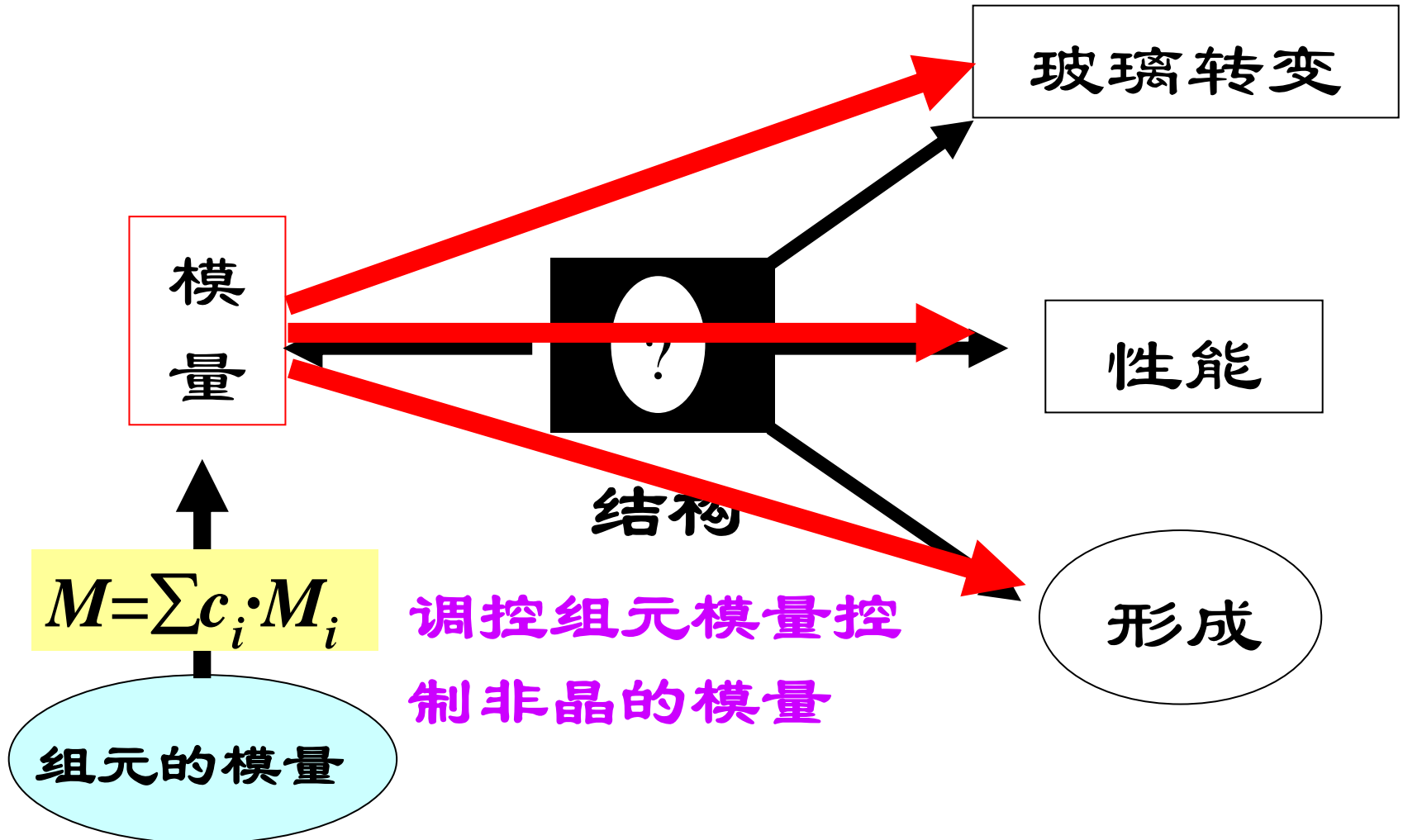
意义:

➤ 对认识、理解非晶的特性和机理至关重要。

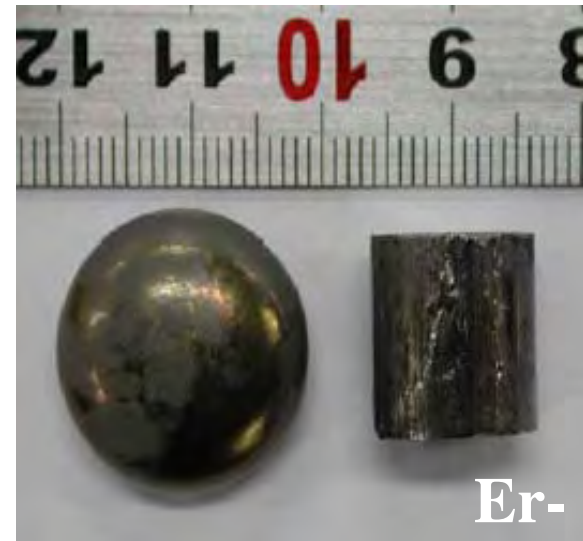
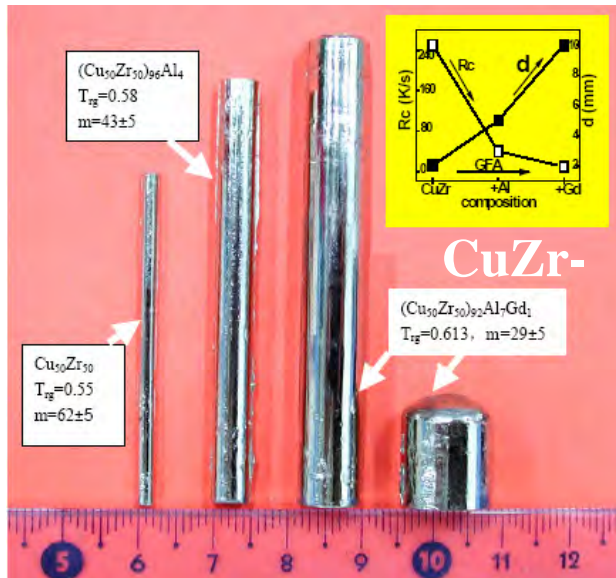
➤ 有助于探索新的非晶材料!

一方面验证弹性模量模型

另一方面：在模量模型的基础上提出控制性能的判据



研制的各类非晶新材料



CuZr-, Ce-, Pr-, Sm-, Gd-, Tb-, Dy-, Ho-,
Er-, Sc-等大块非晶



Adv Mater. 21, 4524 (2009) 功能非晶综述文章

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
1	1 氢 H																	2 氦 He	
2	3 锂 Li	4 铍 Be											5 硼 B	6 碳 C	7 氮 N	8 氧 O	9 氟 F	10 氖 Ne	
3	11 钠 Na	12 镁 Mg											13 铝 Al	14 硅 Si	15 磷 P	16 硫 S	17 氯 Cl	18 氩 Ar	
4	19 钾 K	20 钙 Ca		21 钪 Sc	22 钛 Ti	23 钒 V	24 铬 Cr	25 锰 Mn	26 铁 Fe	27 钴 Co	28 镍 Ni	29 铜 Cu	30 锌 Zn	31 镓 Ga	32 锗 Ge	33 砷 As	34 硒 Se	35 溴 Br	36 氪 Kr
5	37 铷 Rb	38 锶 Sr		39 钇 Y	40 锆 Zr	41 铌 Nb	42 钼 Mo	43 锝 Tc	44 钨 W	45 铑 Rh	46 钯 Pd	47 银 Ag	48 镉 Cd	49 铟 In	50 锡 Sn	51 锑 Sb	52 碲 Te	53 碘 I	54 氙 Xe
6	55 铯 Cs	56 钡 Ba	*	71 镧 La	72 铪 Hf	73 钽 Ta	74 钨 W	75 铼 Re	76 锇 Os	77 铱 Ir	78 铂 Pt	79 金 Au	80 汞 Hg	81 铊 Tl	82 铅 Pb	83 铋 Bi	84 钋 Po	85 砹 At	86 氡 Rn
7	87 钫 Fr	88 镭 Ra	**	103 镧 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Uun	111 Uuu	112 Uub	113 Uuq	114 Uuq	115 Uup	116 Uuh	117 Uus	118 Uuo

- 非金属元素
- 主族金属元素
- 副族金属元素 (过渡金属)

非晶结构材料

21 钪 Sc	22 钛 Ti	23 钒 V	24 铬 Cr	25 锰 Mn	26 铁 Fe	27 钴 Co	28 镍 Ni	29 铜 Cu	30 锌 Zn
39 钇 Y	40 锆 Zr	41 铌 Nb	42 钼 Mo	43 锝 Tc	44 钨 W	45 铑 Rh	46 钯 Pd	47 银 Ag	48 镉 Cd
71 镧 La	72 铪 Hf	73 钽 Ta	74 钨 W	75 铼 Re	76 锇 Os	77 铱 Ir	78 铂 Pt	79 金 Au	80 汞 Hg

57 镧 La	58 铈 Ce	59 镨 Pr	60 钕 Nd	61 钷 Pm	62 钐 Sm	63 铕 Eu	64 钆 Gd	65 铽 Tb	66 镝 Dy	67 钬 Ho	68 铒 Er	69 铥 Tm	70 镱 Yb
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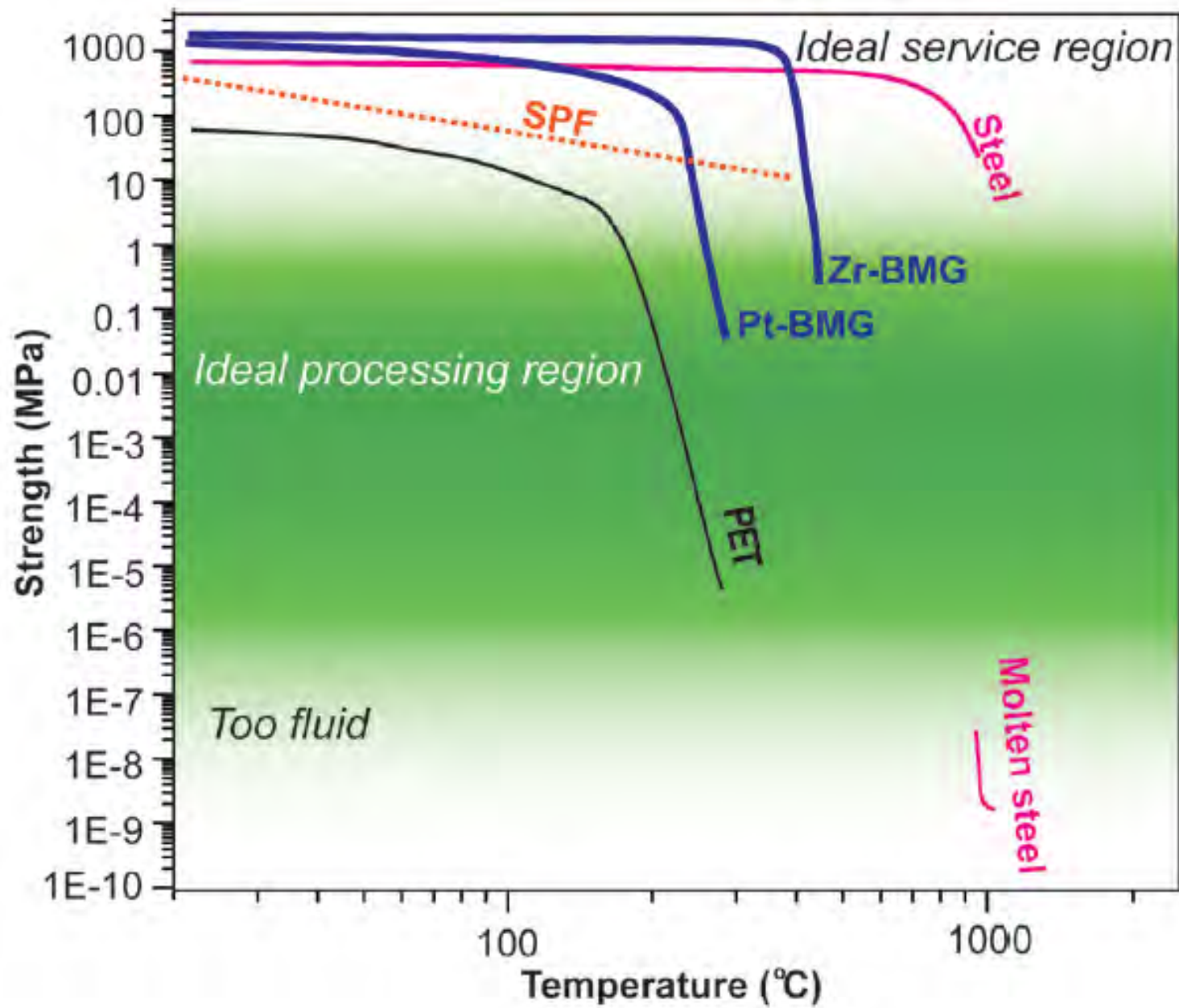
* 镧系元素

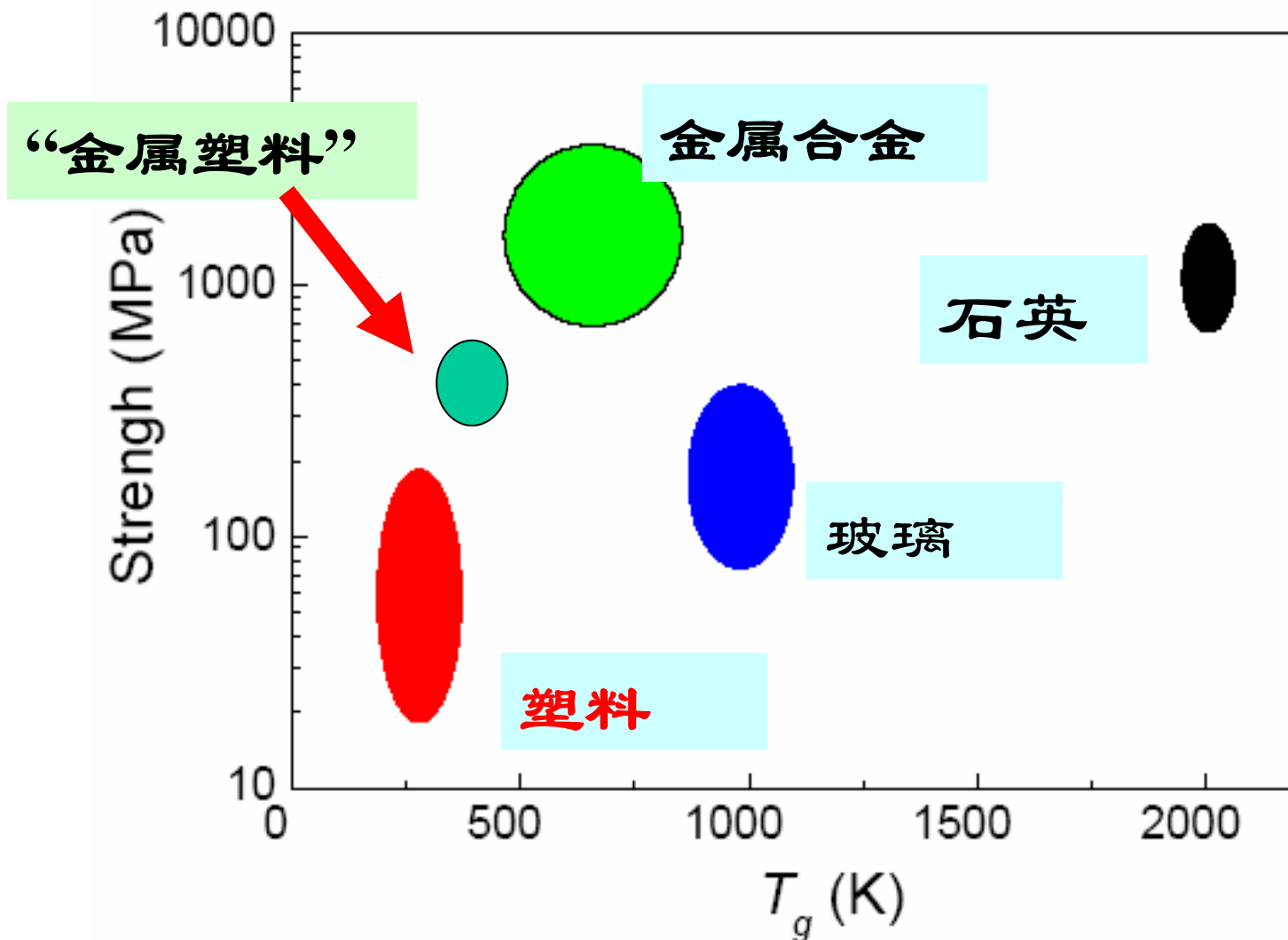
** 锕系元素

新型稀土非晶材料

2、 新材料的获得

— — 金属塑料





金属和塑料是应用最广泛的两类材料

能否得到结合塑料的热塑性和金属材料
的优异力学性能的材料???

可在过冷液相区进行超塑性加工形变是非晶合金的重要特性

要求低的玻璃转变温度 T_g ，粘滞系数小，液体脆性系数大

$$E \propto T_g$$

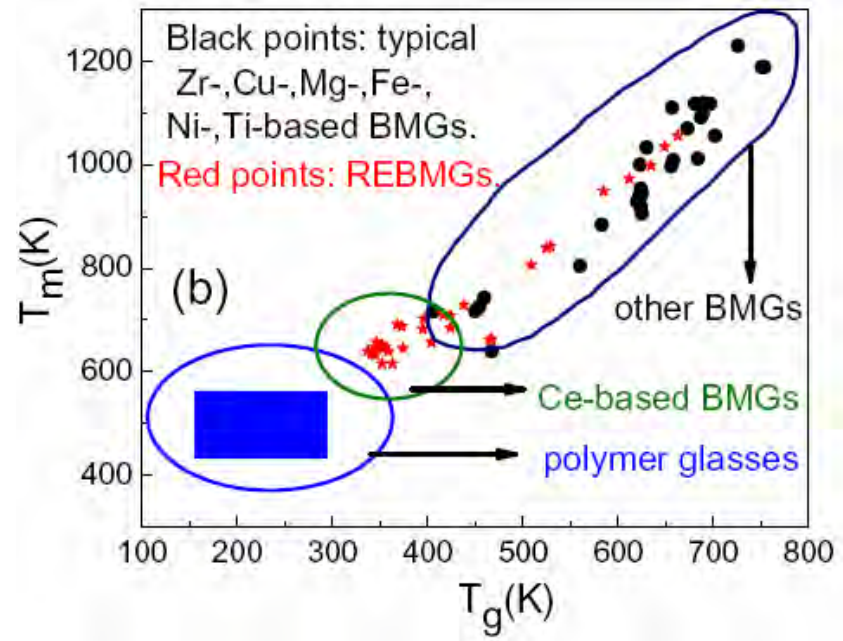
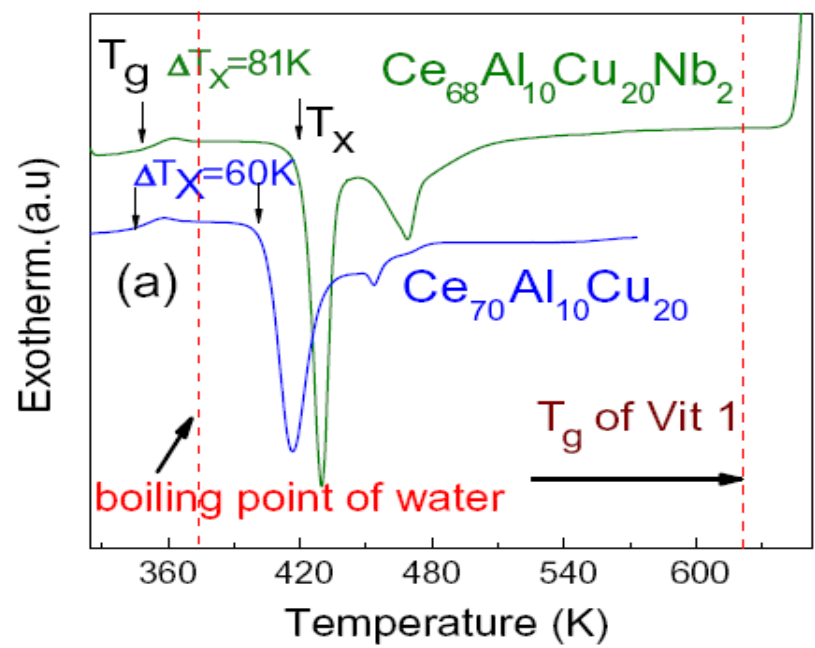
要探索低 T_g 的非晶，可探索低模量的非晶合金



玻璃超塑性成型技术
是一门艺术



金属塑料 (低T_g 块体非晶合金)



与塑料类似点1：很强的非晶形成能力

类似点2：很高的稳定性



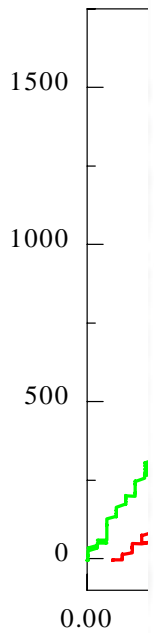
Phys Rev Lett. 94, 205502(2005)

被选为Phys. Rev. Focus 9 June 2005;

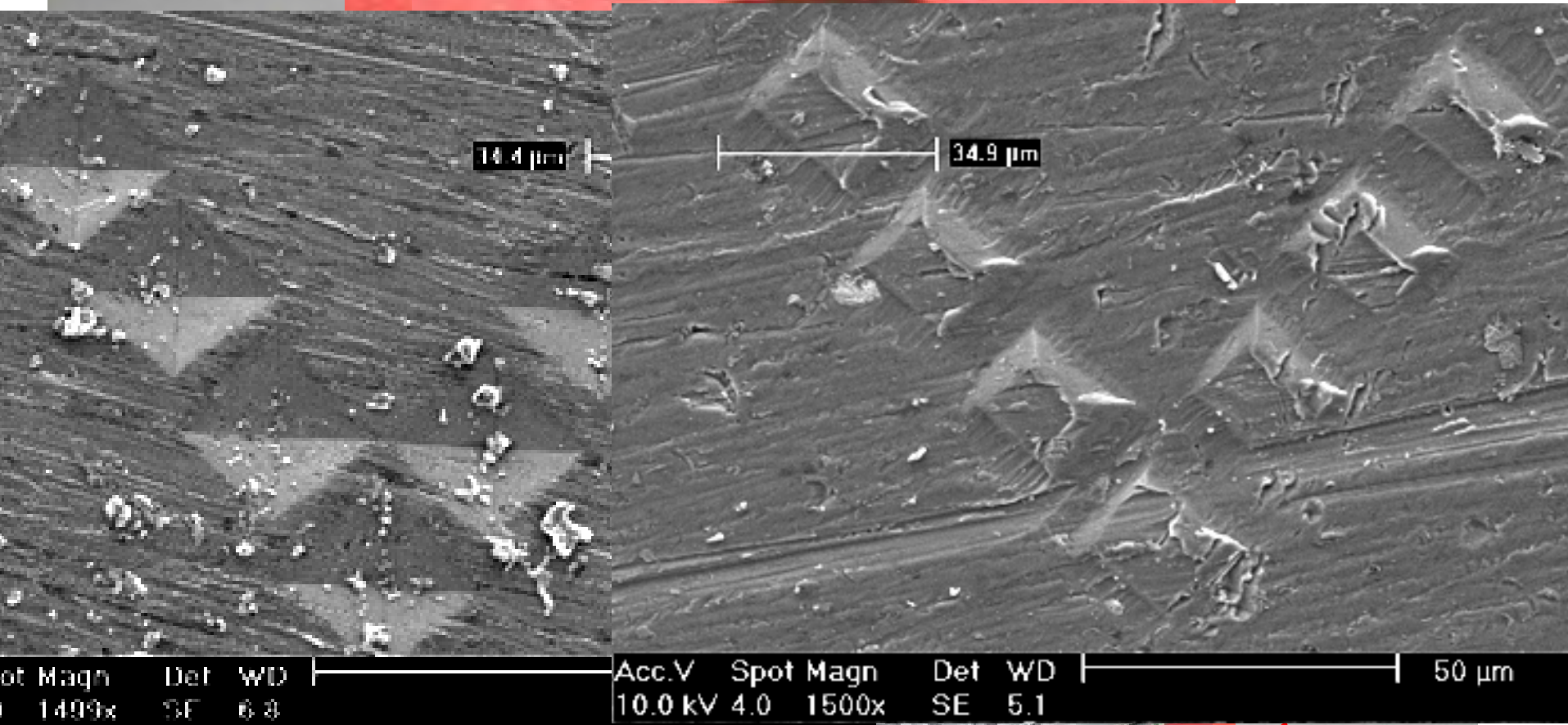
Nature, Highlight, Vol 435, pp.717, 2005

Parameter	Materials		
	Plastics	BMG	SPF alloys
Processing temperature [°C]	160-260°C	160°C (Au-based) 280°C (Pt-based) 350°C (Pd-based) 430°C (Zr-based)	900°C (Ti ₆ Al ₄) ¹⁸ 465°C (Al 2004)
Processing pressure [Pa]	1-10 x 10 ⁵ Pa	1-4 x 10 ⁵ Pa	1-4 x 10 ⁵ Pa
Maximum strain	∞	~10 000%	< 400%
Typical strain rate [s ⁻¹]	10 ⁻¹ -1	10 ⁻¹	10 ⁻³
m	~1	1	0.4-0.7
$ms = \left. \frac{d \log(h/G)}{dT_g/T} \right _{T=T_g}$	137 ²⁰	52 (Pt-based) ²¹ 70 (Zr-based) ²¹	Not applicable
κ [W/mK]	0.3	10	170

Stress (MPa)



金属加工的新模式！

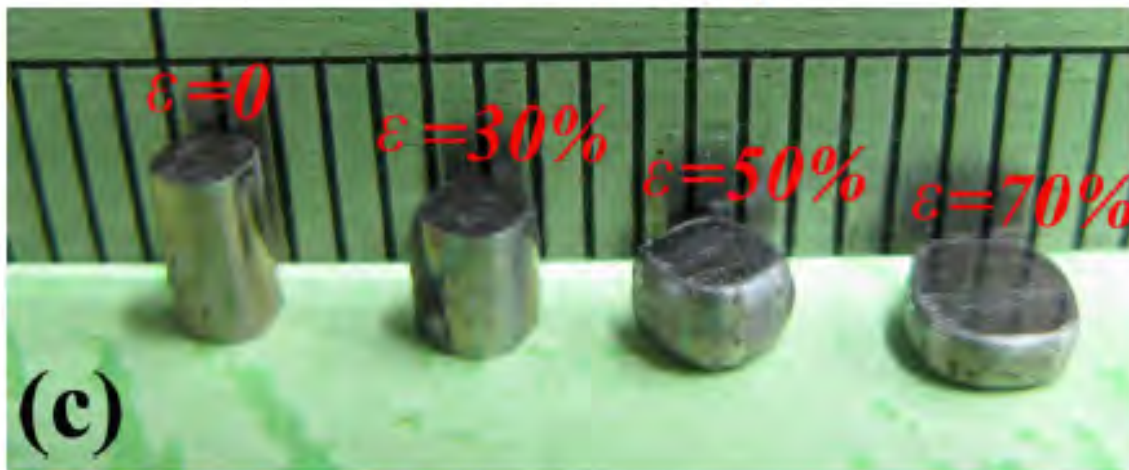
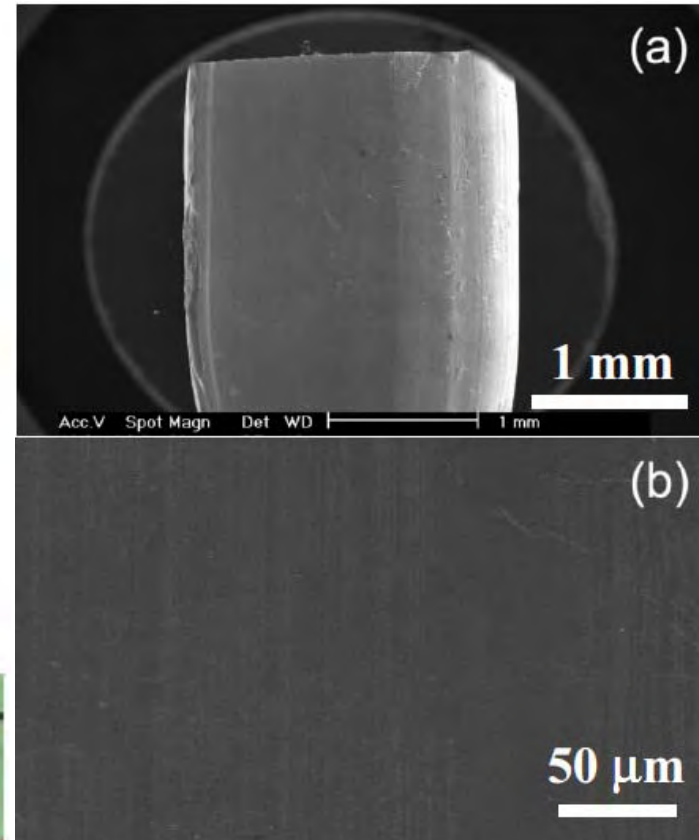
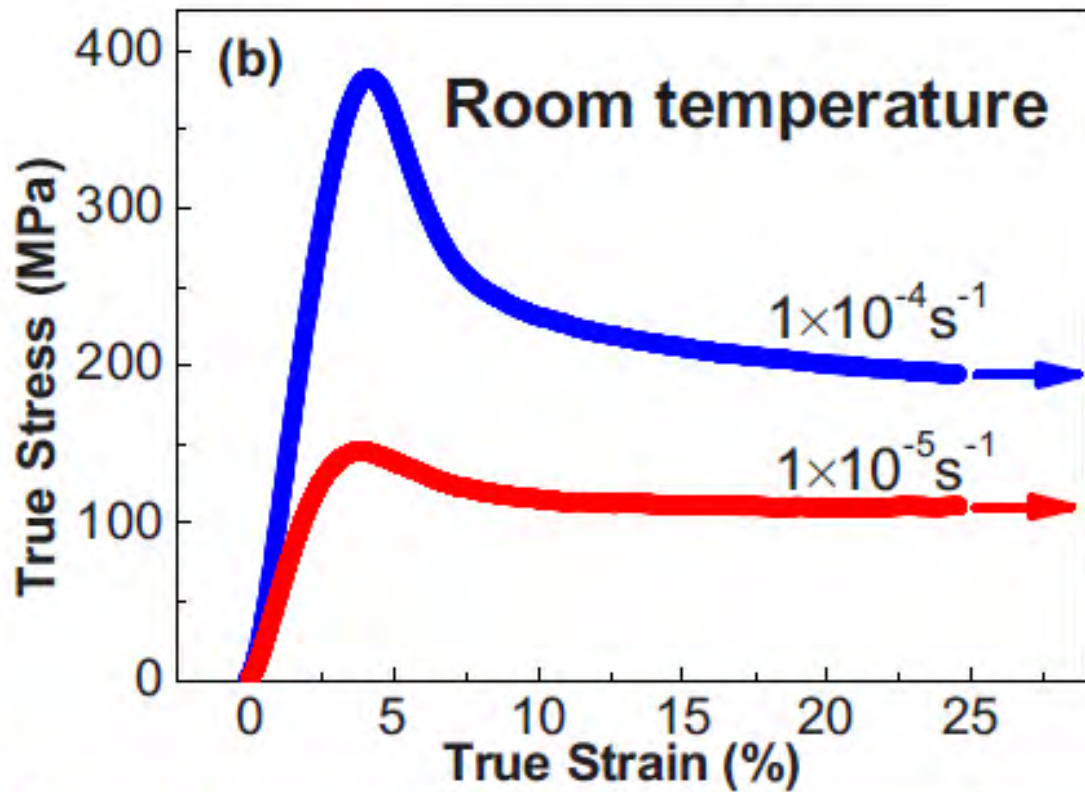


$$T_g < T_{pe}$$

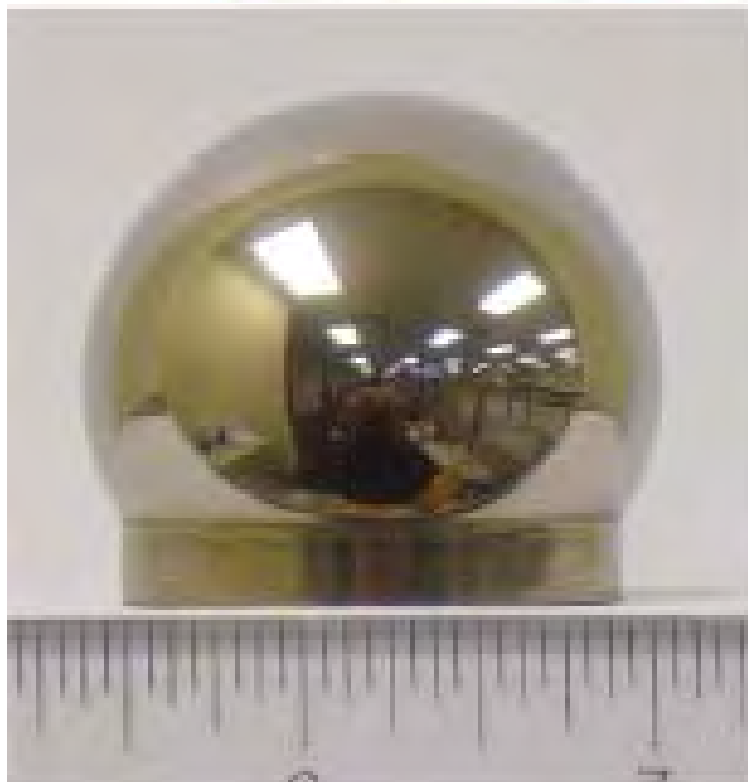
成型
写、变形

PRL, 94, 205501 (2005)

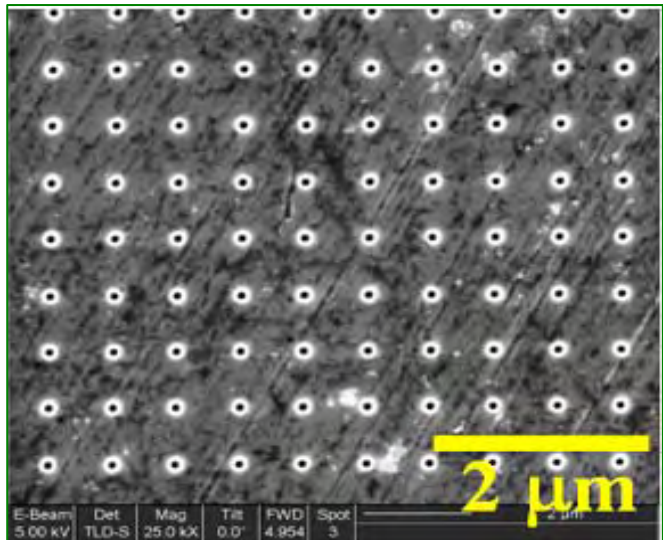
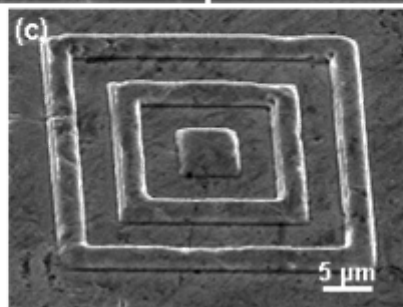
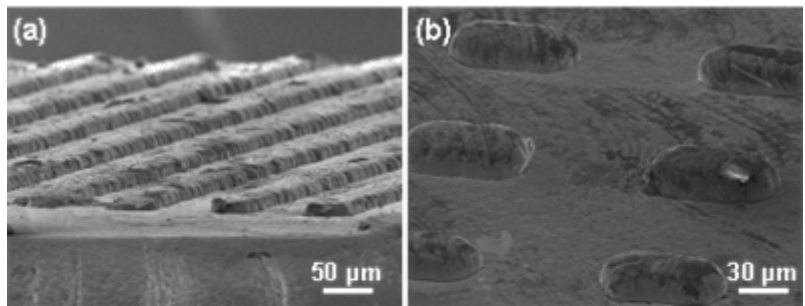
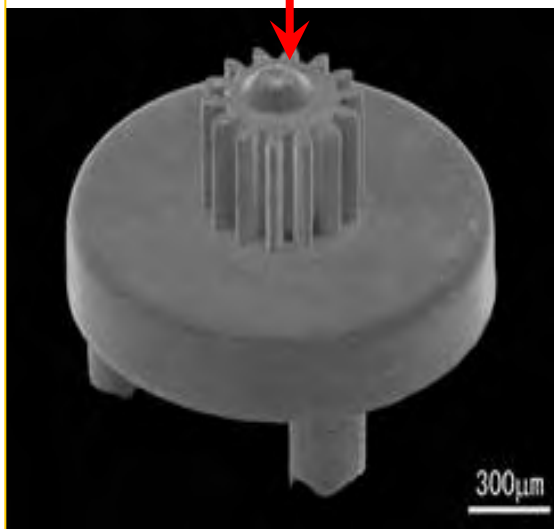
”柔软“的金属玻璃



Appl Phys Lett 2011

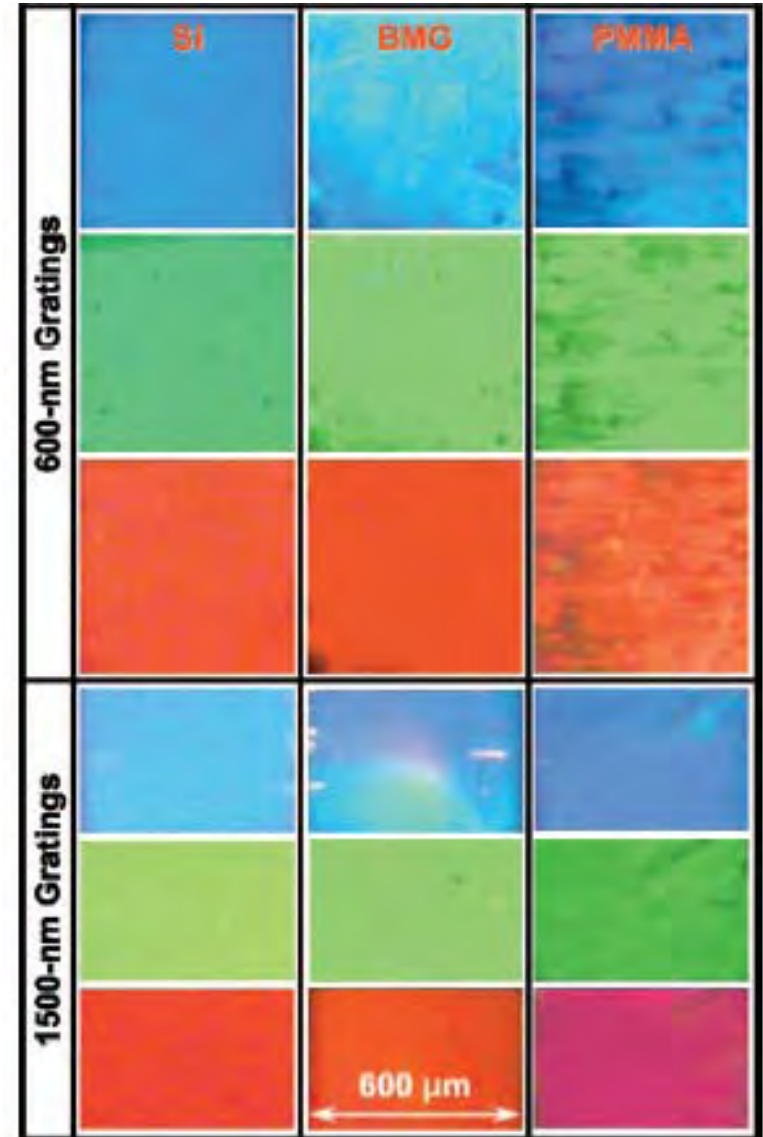
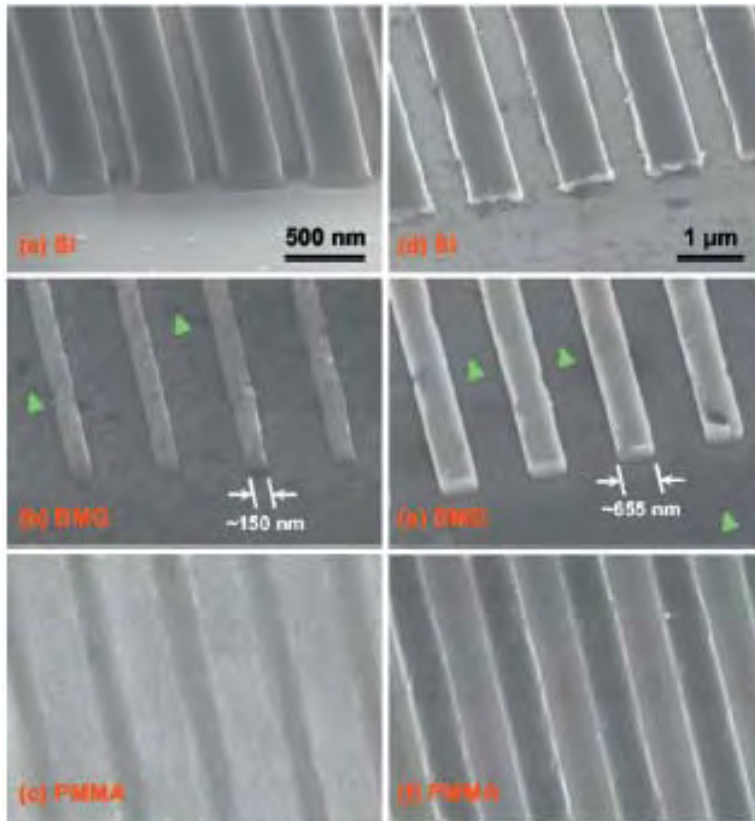


“金属塑料”是微/纳米级加工、成型的候选材料



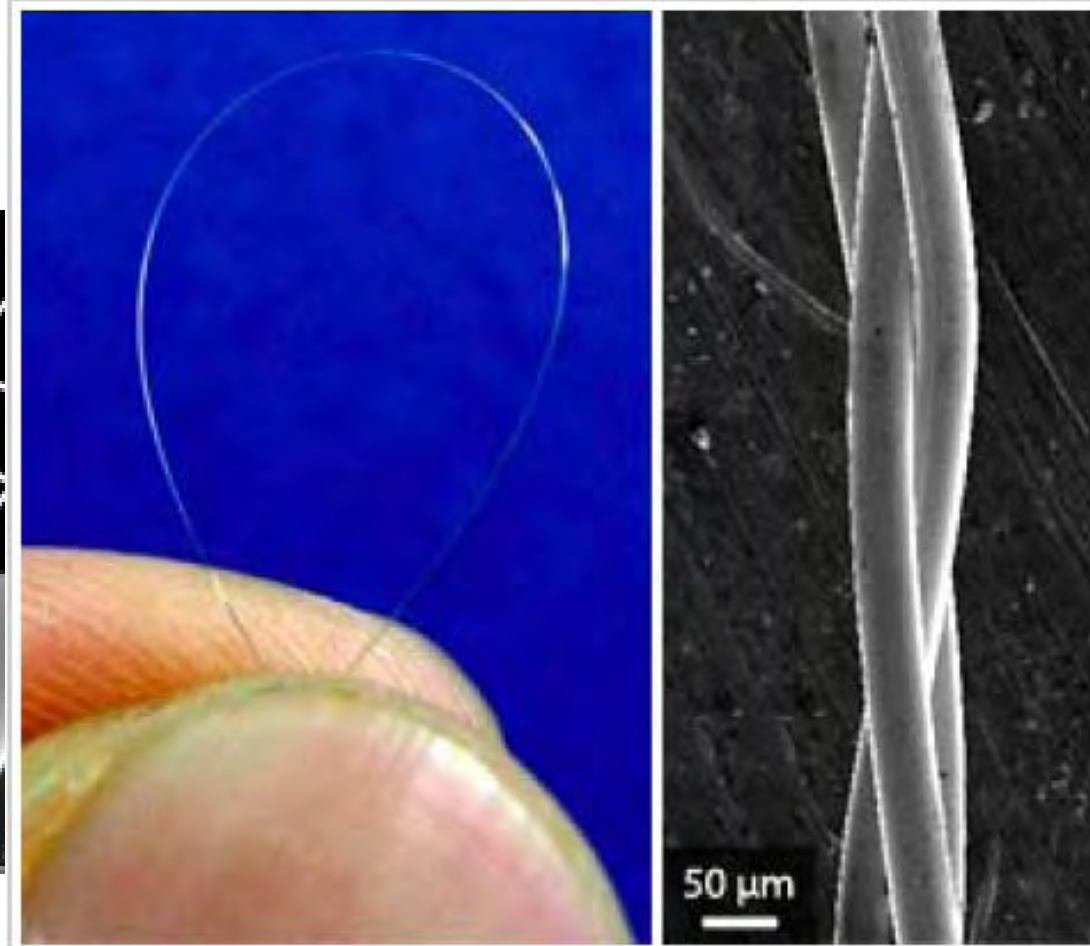
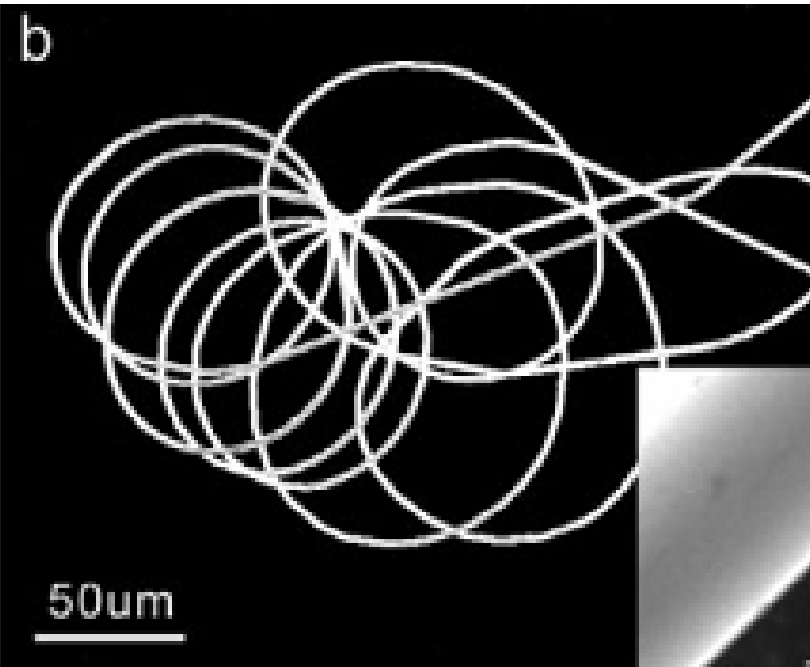
A promising material for microdevices

金属塑料光栅



microforming of
Ce glass at 420K

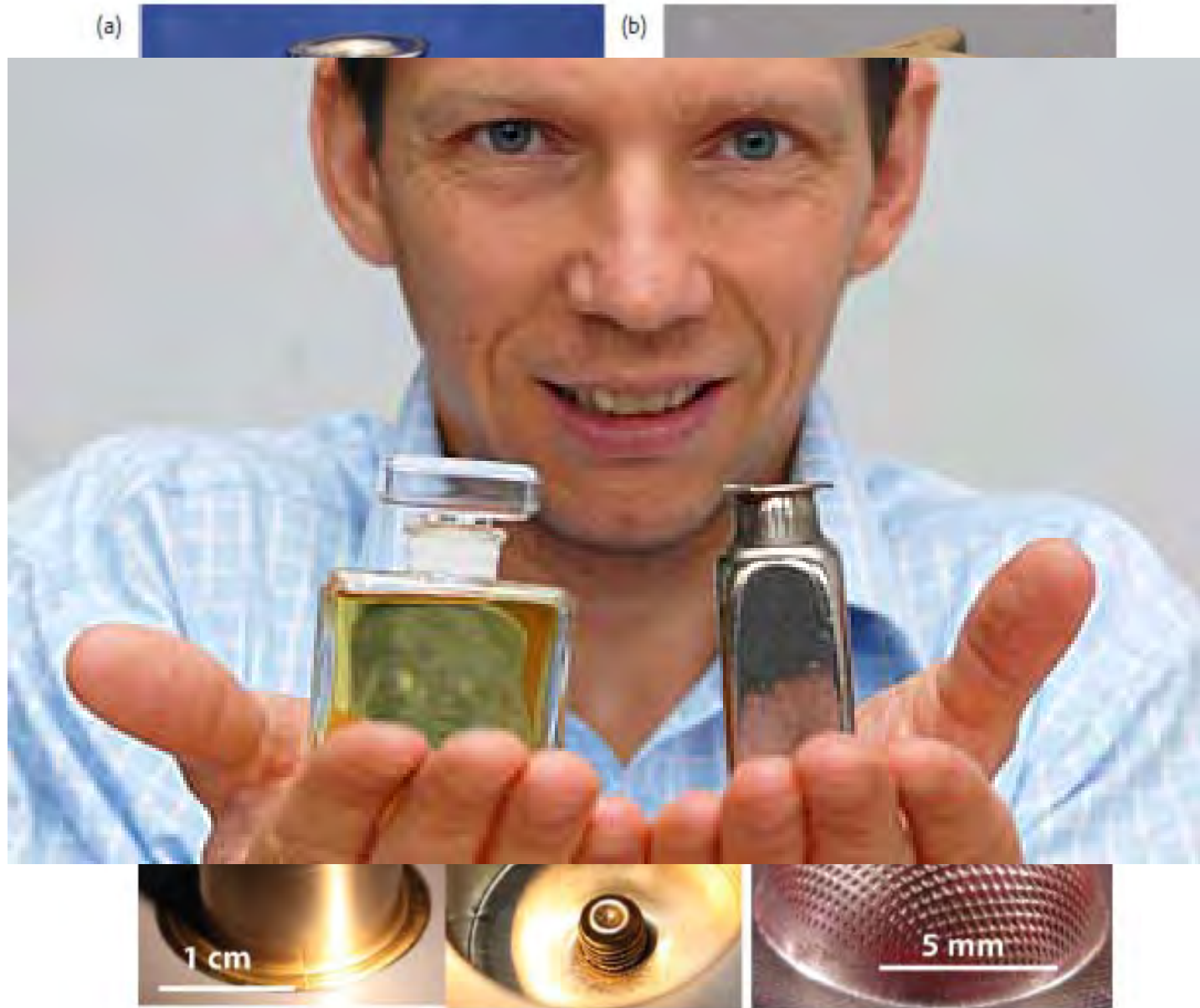
微纳级非晶丝

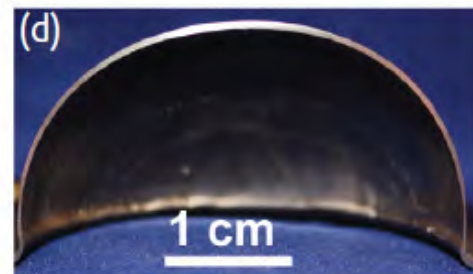
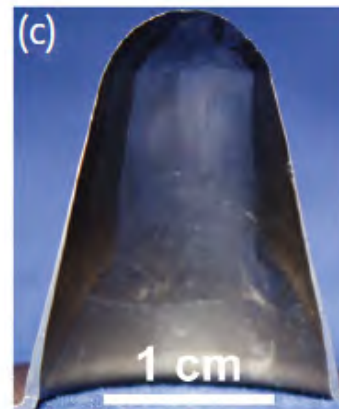
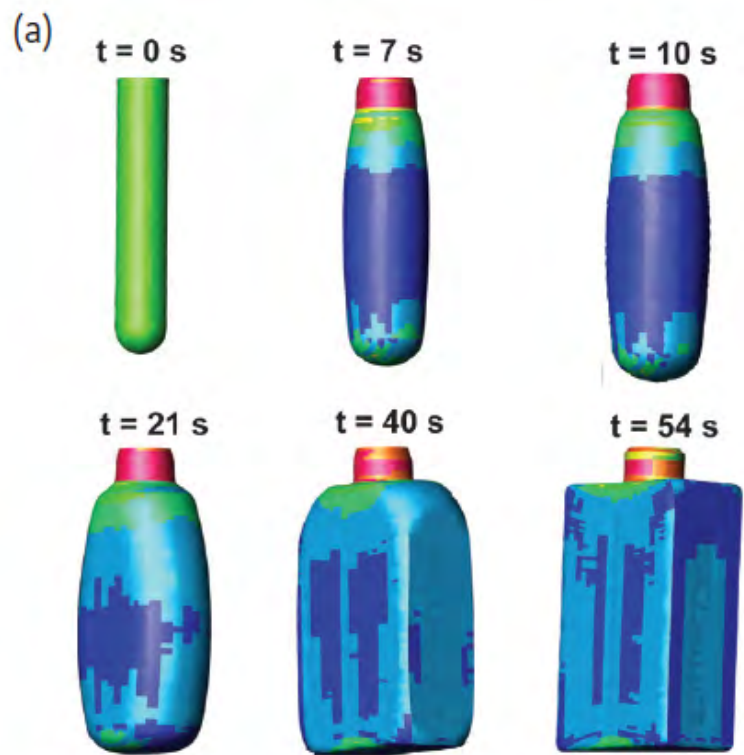


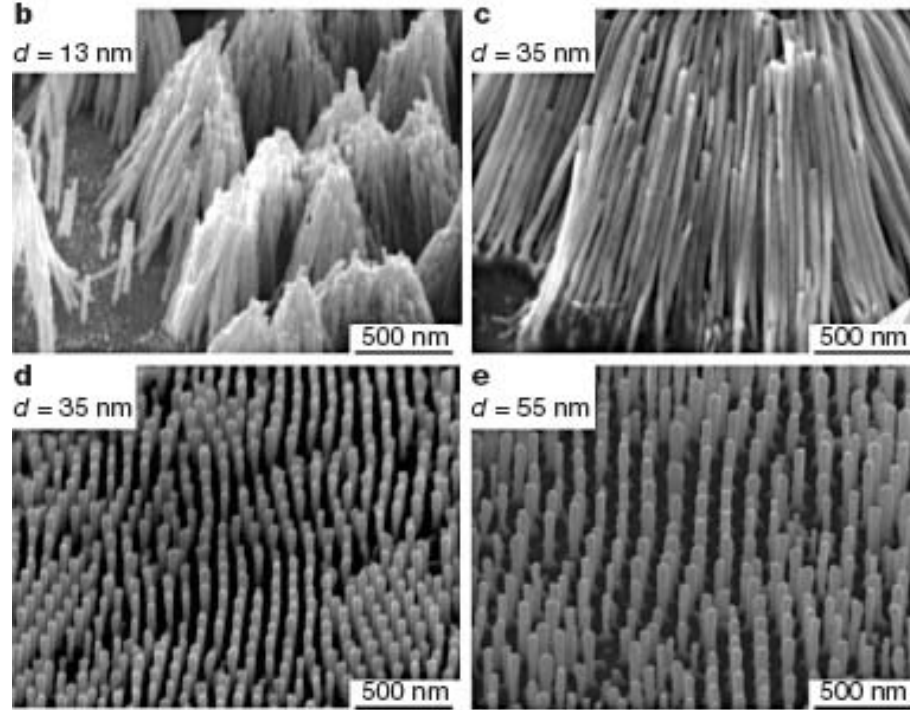
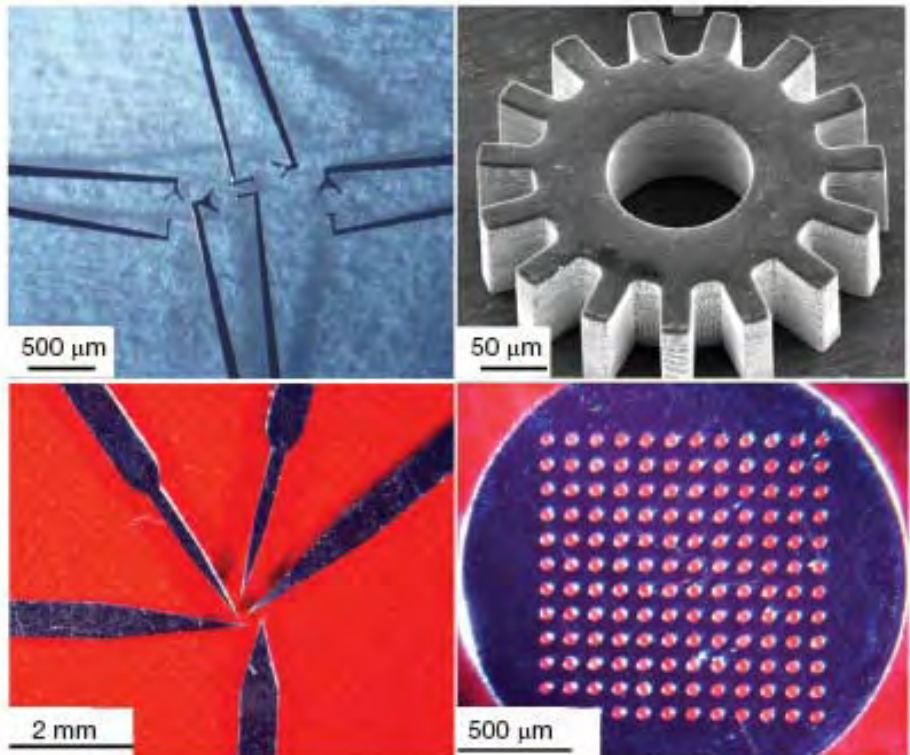
微纳米级非晶丝：具有很好的拉阻效应，能够用作拉力传感器，位移传感器等的工作元件。

Adv Eng Mat 2010

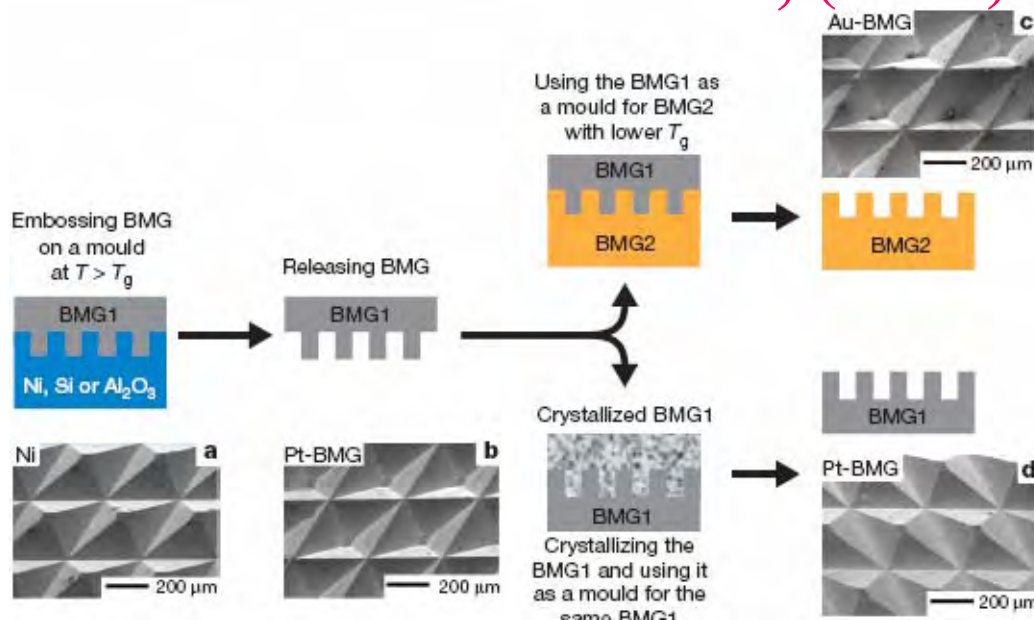
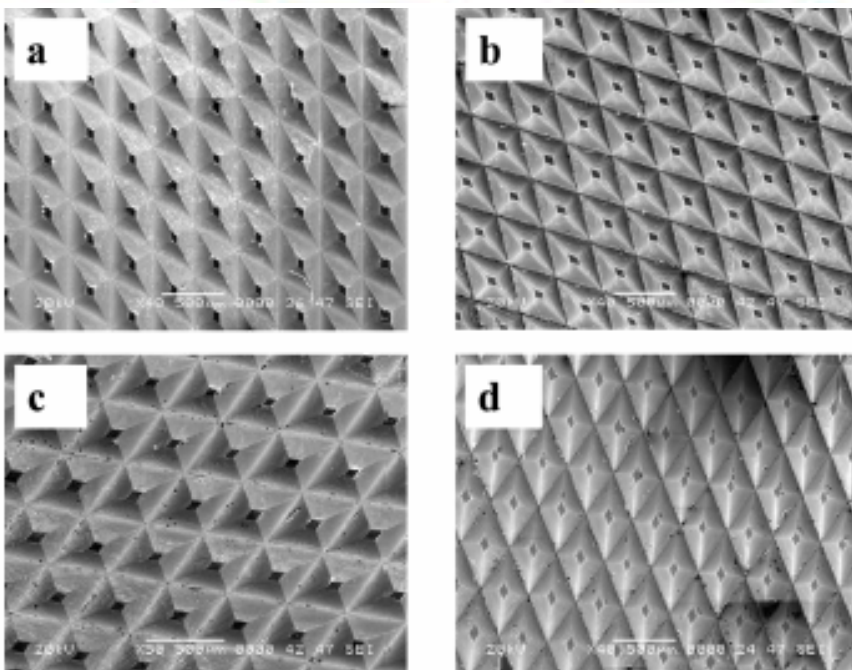
金屬加工的全新模式





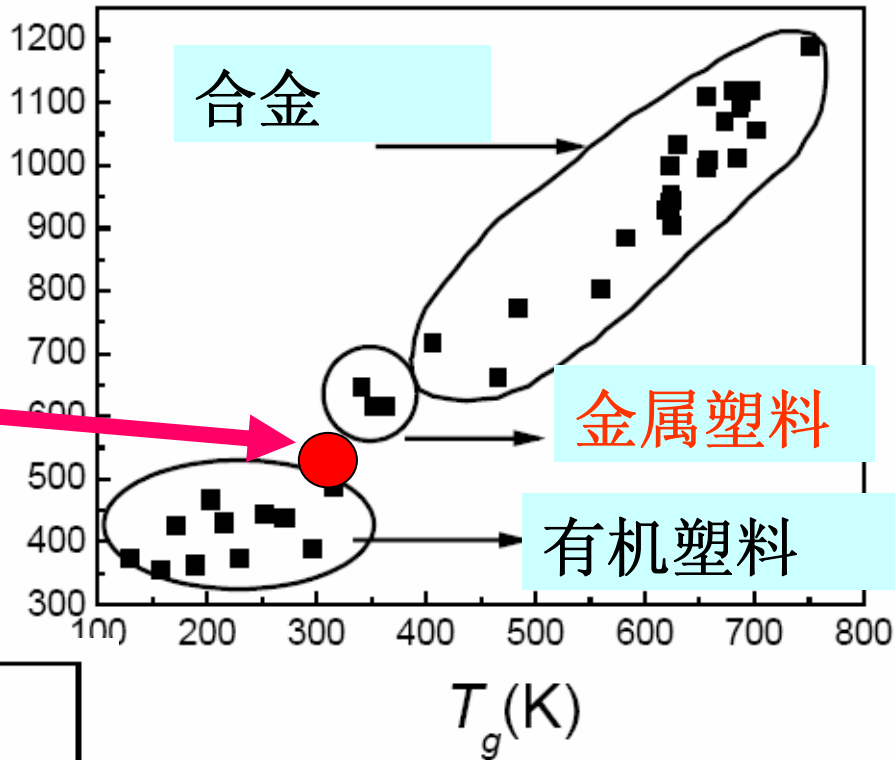


Schrores Nature 457, (2009)



金属塑料

T_m (K)

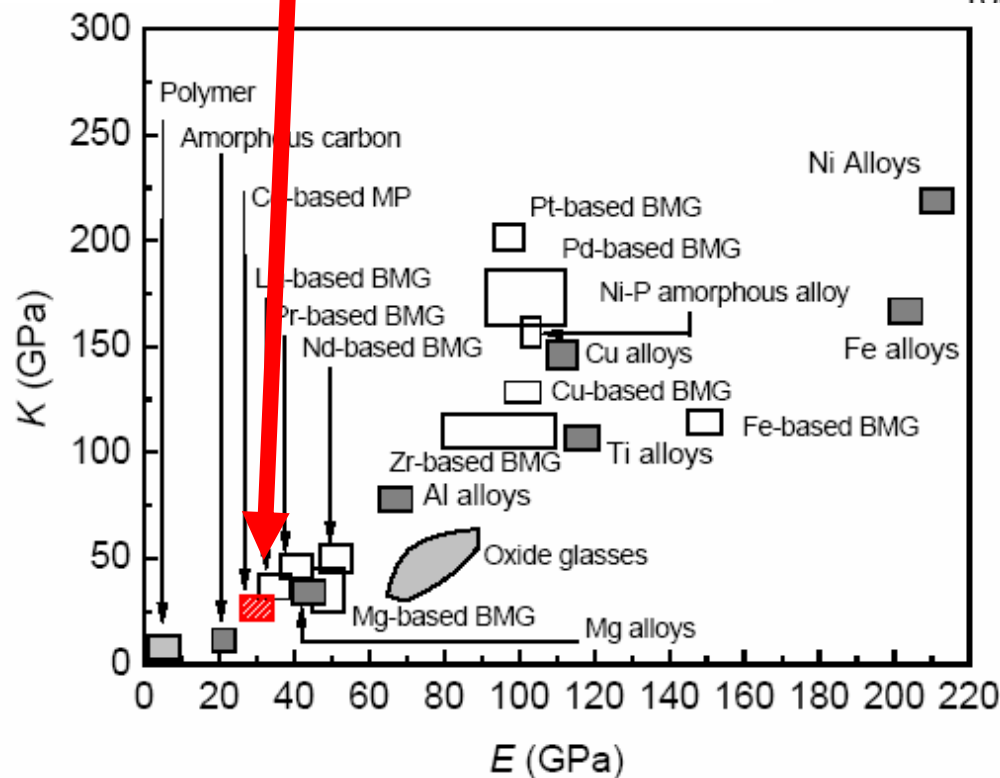


金属塑料

有机塑料

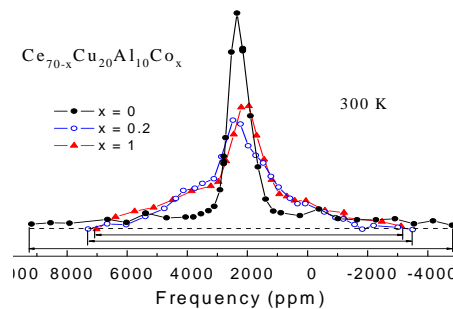
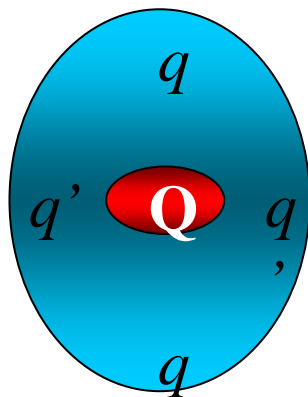
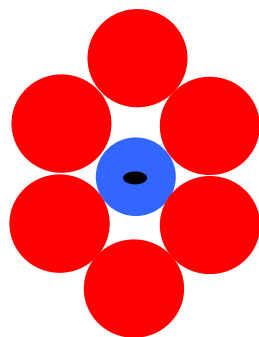
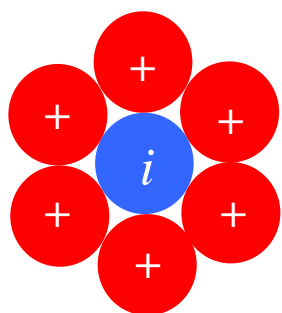
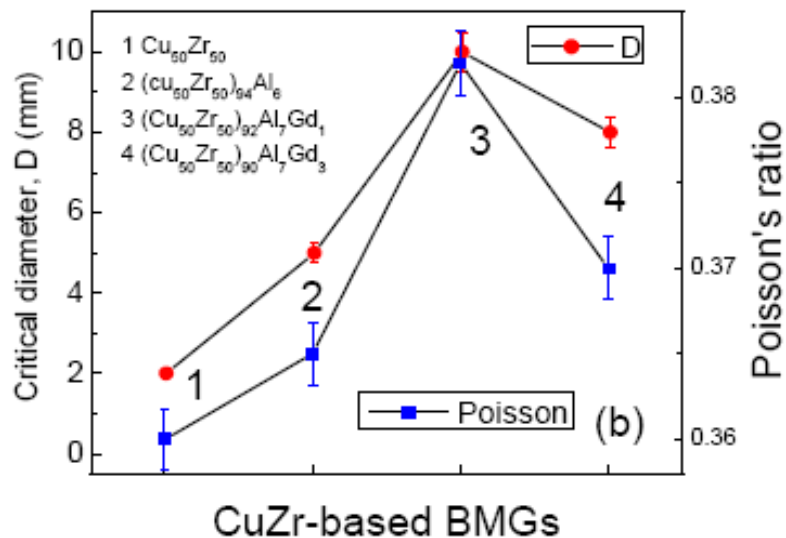
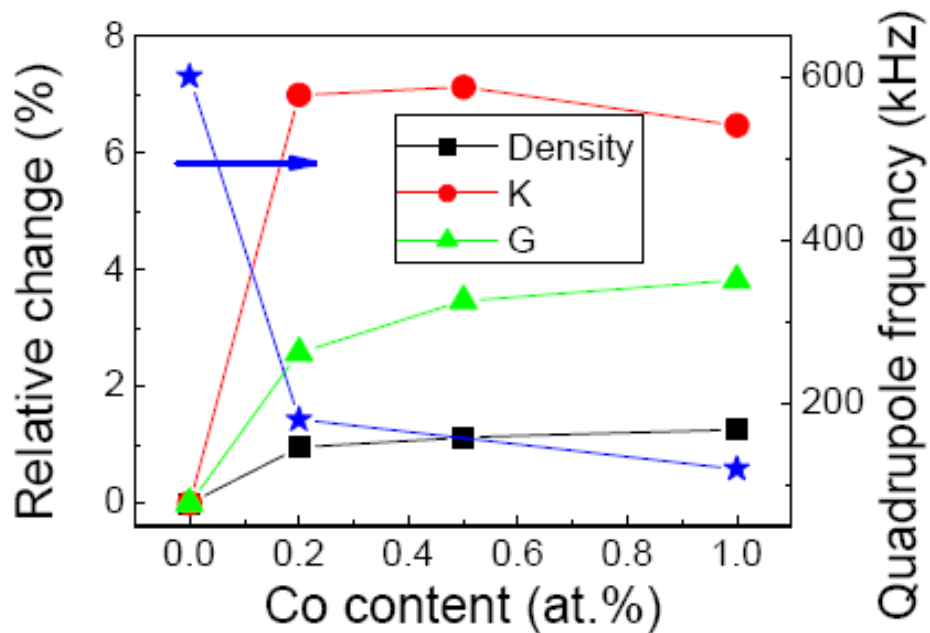
T_g (K)

该类材料结合了金属和塑料的重要特性



E (GPa)

物理机制和结构原因研究



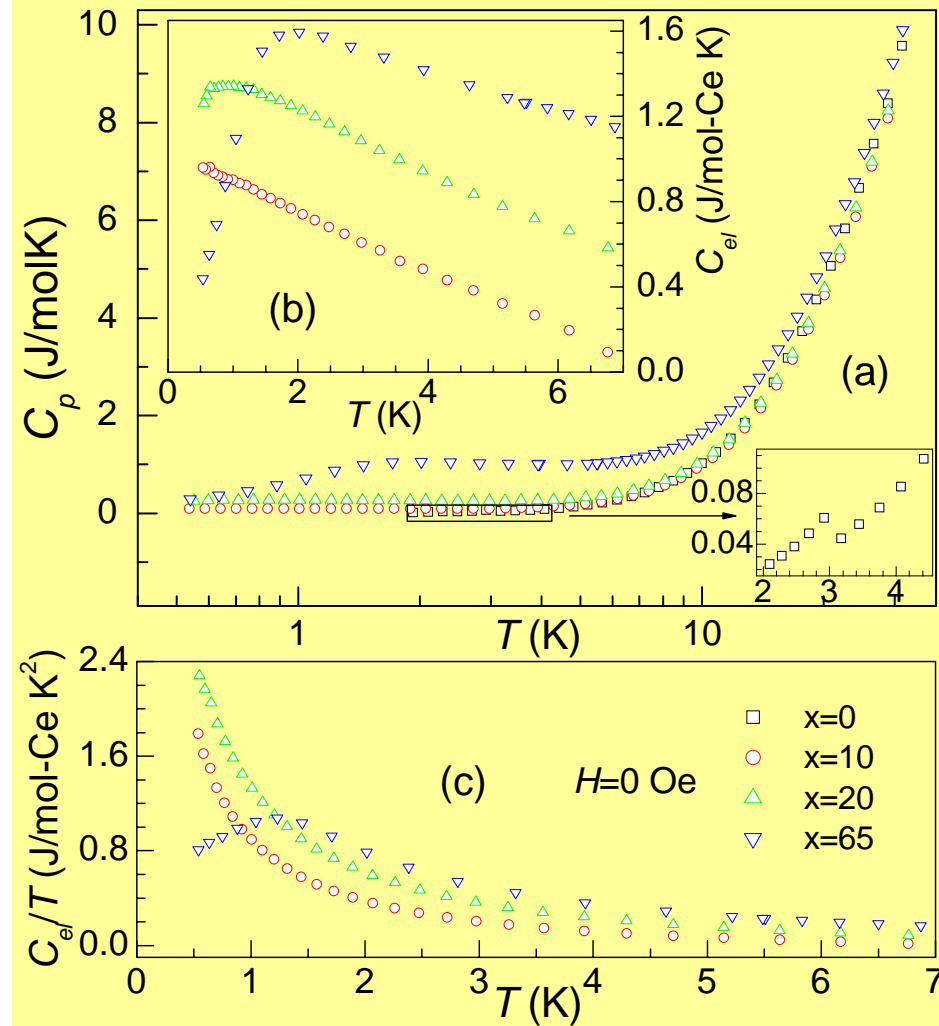
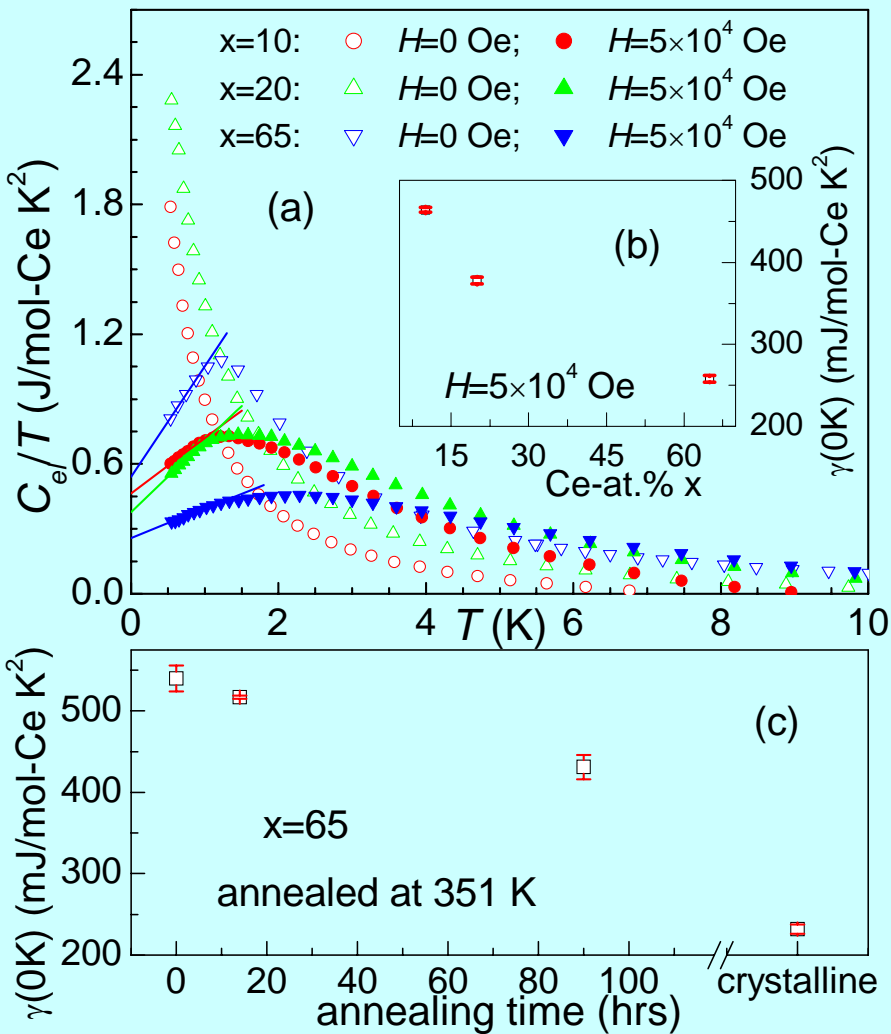
Phys. Rev. Lett. 99, 095501 (2007)

引发新的工作

PNAS 2007

Nature Mater 2007

Heavy electron 金属玻璃

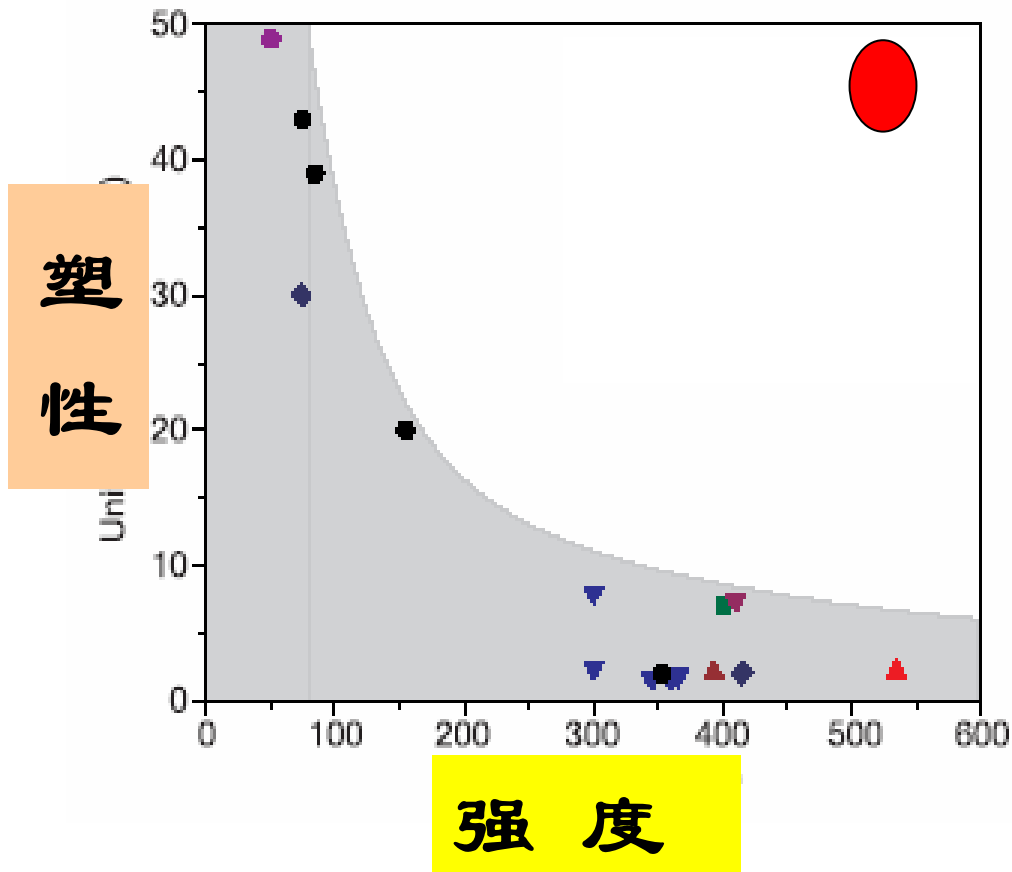


Nature Mater, 6, 181(2007) 以“Changing the face of the glasses”评价该项工作

3、高强度、大塑性的 非晶材料

强度和塑性

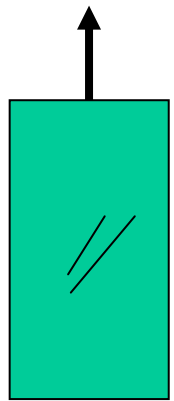
强度和塑性是一对矛盾体，提高强度和塑性是古老而永恒的题目



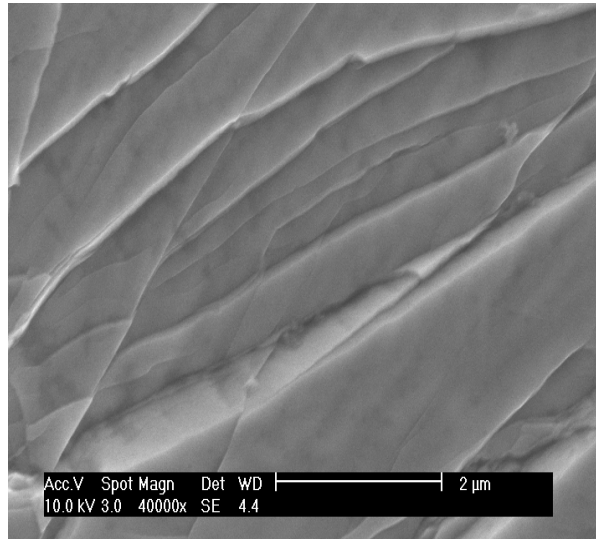
美国：钢强度提高5%，
桥梁寿命增加1%，
效益达300亿US\$

传统理论认为非晶脆性是本征的

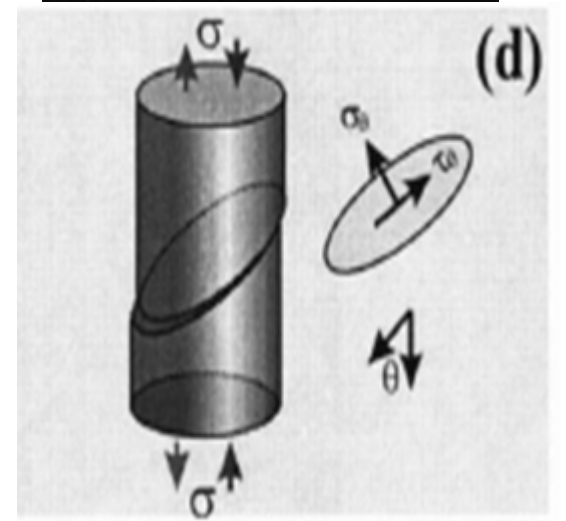
非均匀形变 \longrightarrow **剪切带** \longrightarrow 脆性



Force



剪切带模型



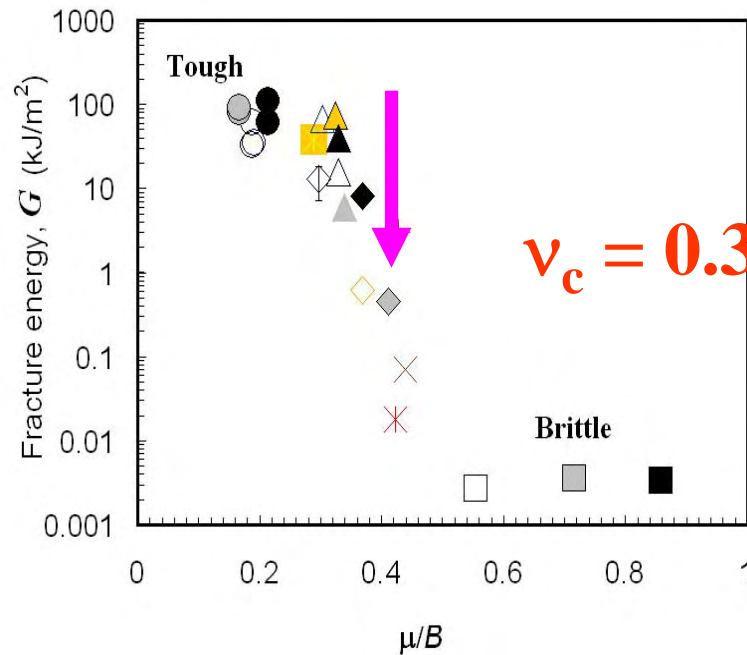
提出塑性和泊松比联系的模量判据

❖ 一些非晶合金有塑性

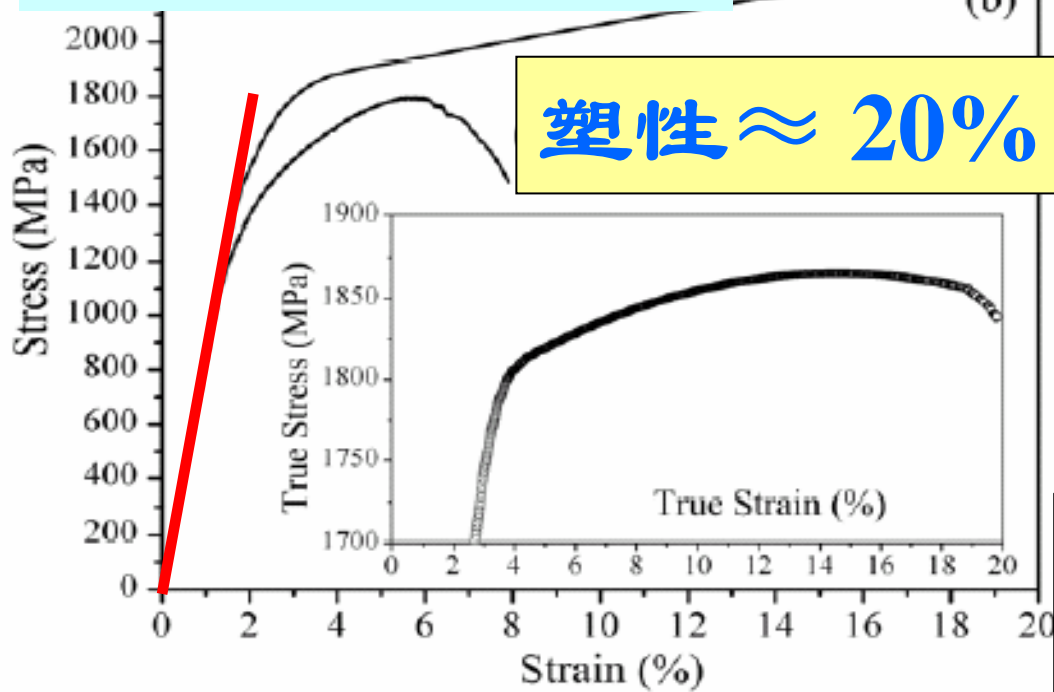
❖ 对剪切带的控制可改进非晶塑性

❖ 极高密度的剪切带 → 近均匀形变

如何产生
极高密度
剪切带？



CuZrAl 大块非晶



强度 = 2.23 GPa



Physical Review
Focus

[Focus Archive](#) [PNU Index](#) [Image Index](#) [Focus Search](#)

[Previous Story](#) / [Next Story](#) / [January - June 2005 Archive](#)

[Phys. Rev. Lett. 94, 205501](#)
(issue of 27 May 2005)
[Phys. Rev. Lett. 94, 205502](#)
(issue of 27 May 2005)
[Titles and Authors](#)

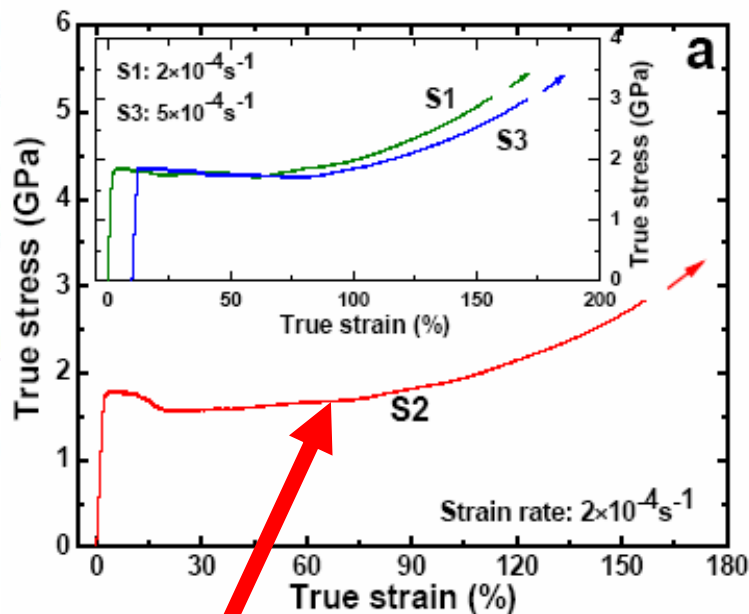
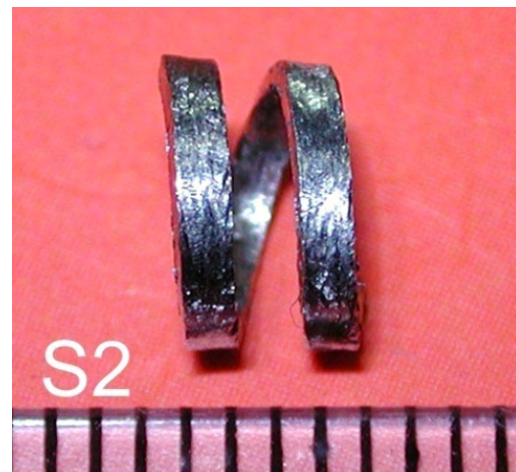
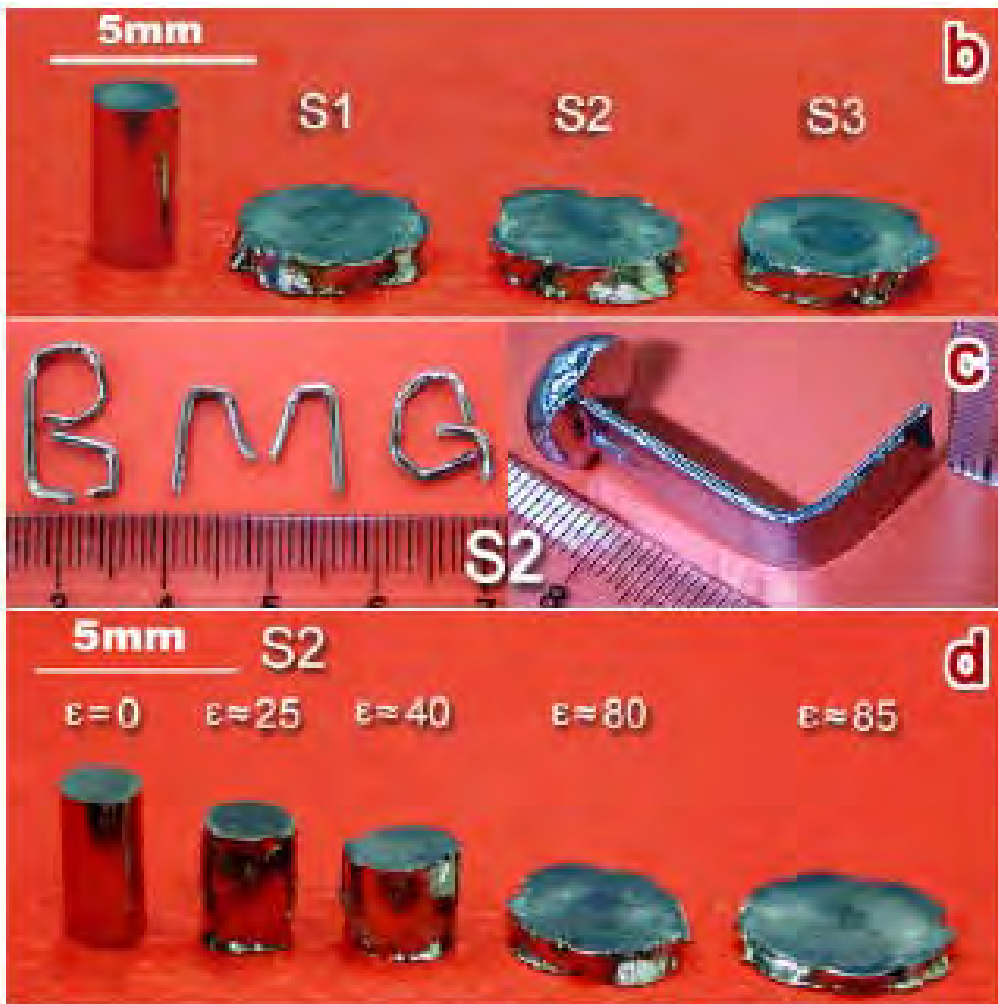
9 June 2005

Glass-Like Metal Performs Better Under Stress

➤ Phys Rev. Lett. 2005, 94, 205501 (2005) Chin
Phys. Lett (2004) 901

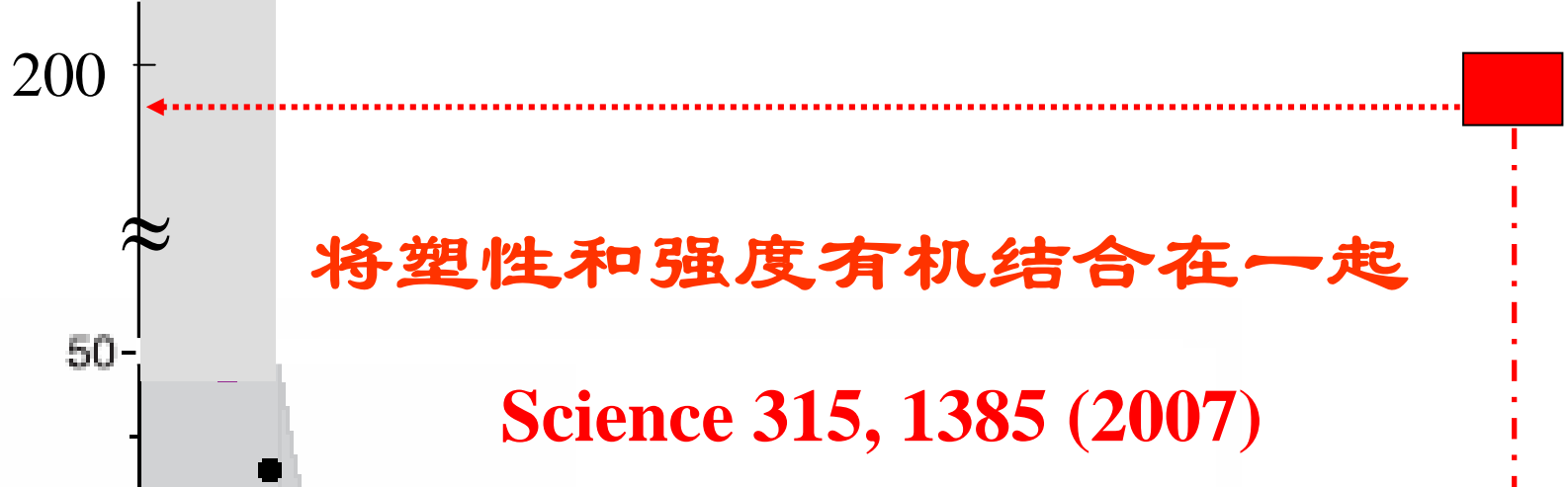
➤ 被PRL选作Focus

大压缩塑性、高强度非晶合金材料的获得

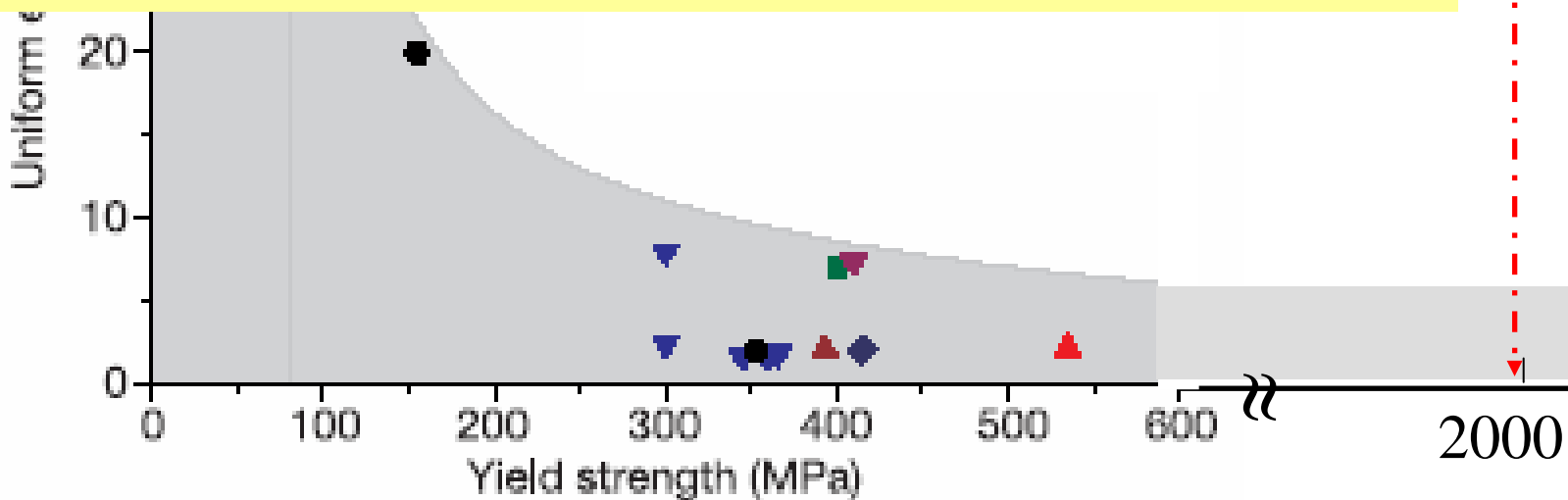


压缩塑性 > 30%

Science 315, 1385(2007)



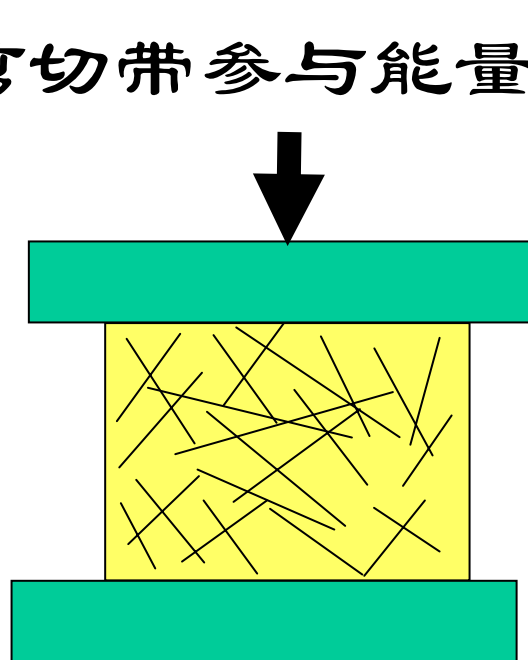
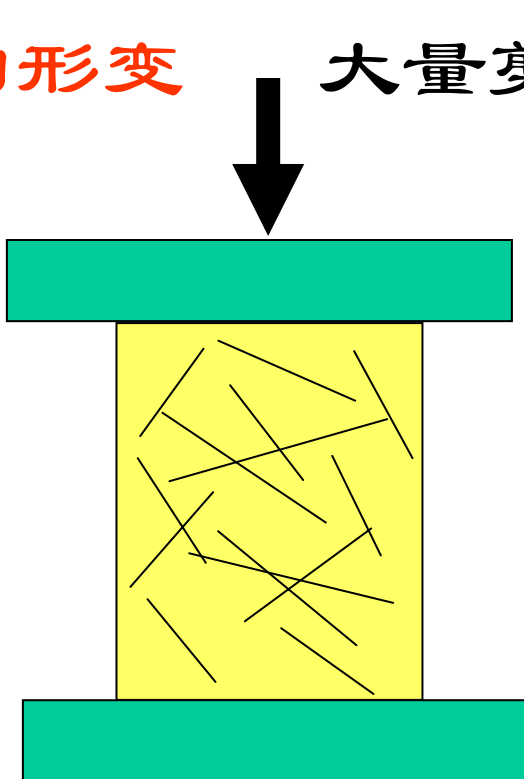
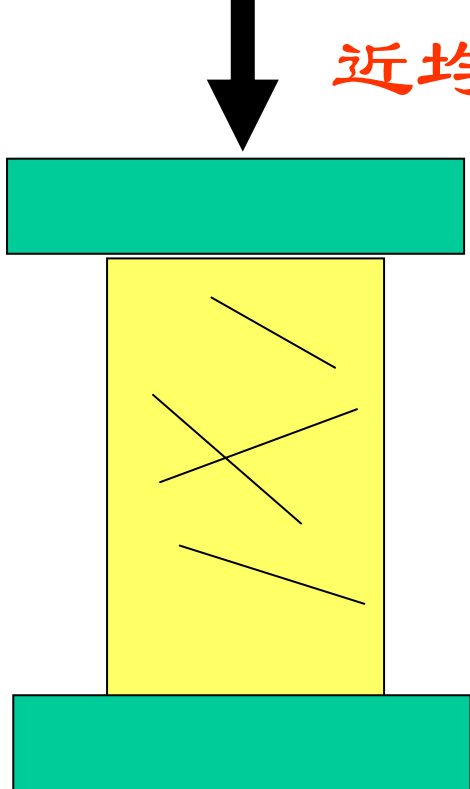
超强金属玻璃：3毫米直径
粗棒可撑起2吨重小汽车



与其它材料的力学性能比较

近均匀形变

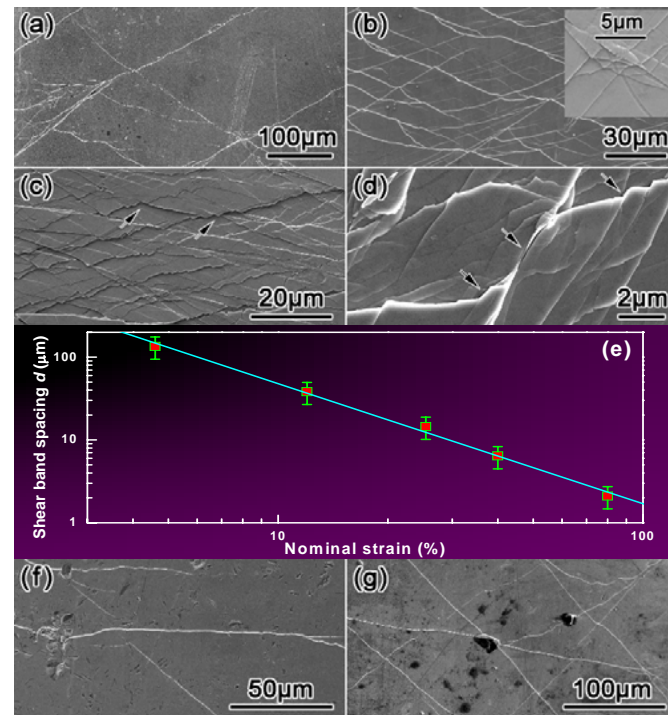
大量剪切带参与能量耗散



$$d = A \varepsilon^{-B}$$

$$B = 1.45$$

ε (%)	Shear band spacing d (μm)
4.6	135
12	38.2
25.4	14.5
40	6.4
80	2.1



大量、高密度剪切带产生
特殊的结构



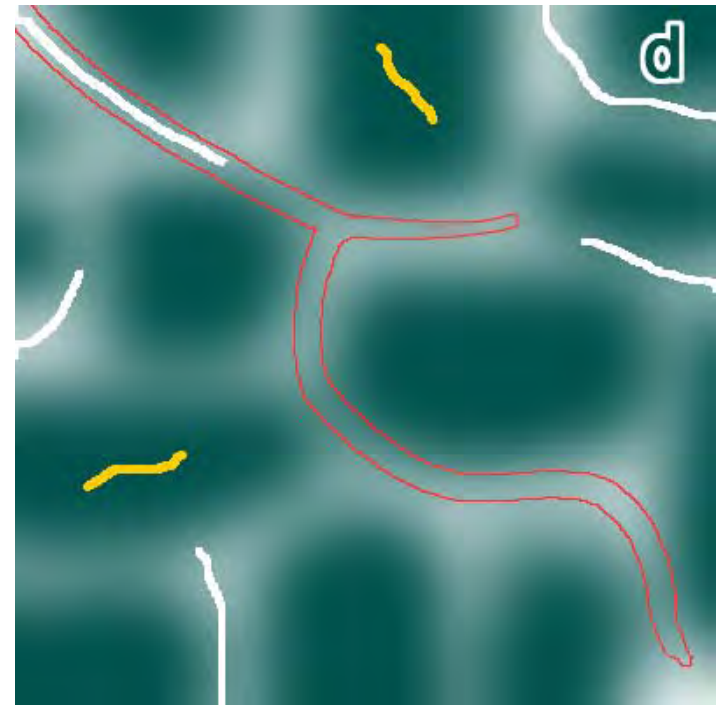
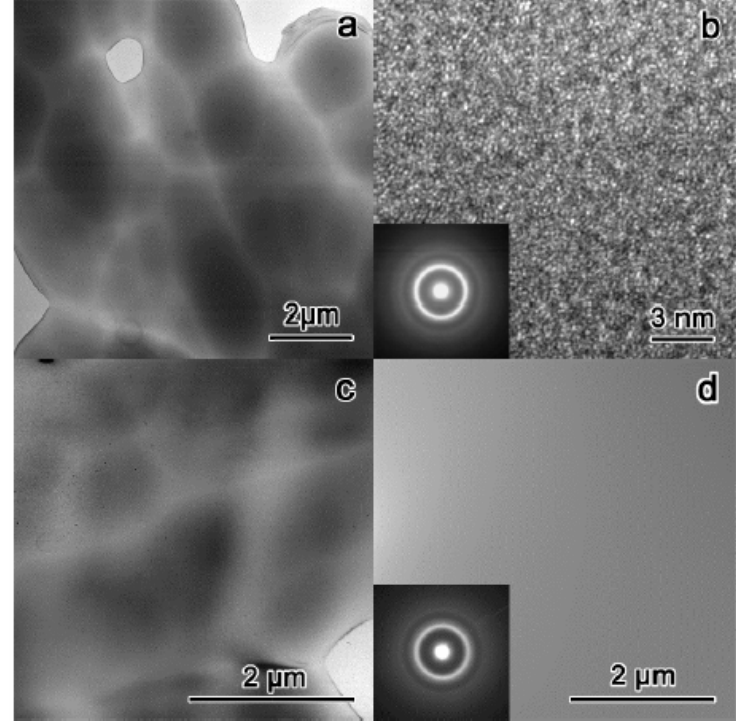
超大塑性

提出硬/软区增塑方法

Science 315, 1385 (2007)

软区：造成大量剪切带，耗散能量

硬区：阻止剪切带发展成裂纹，提高强度



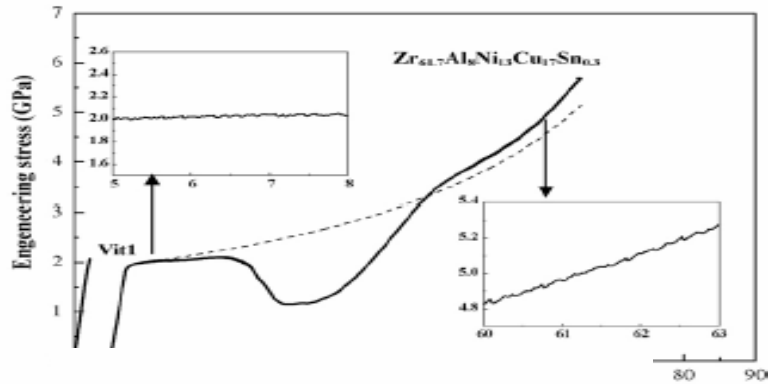
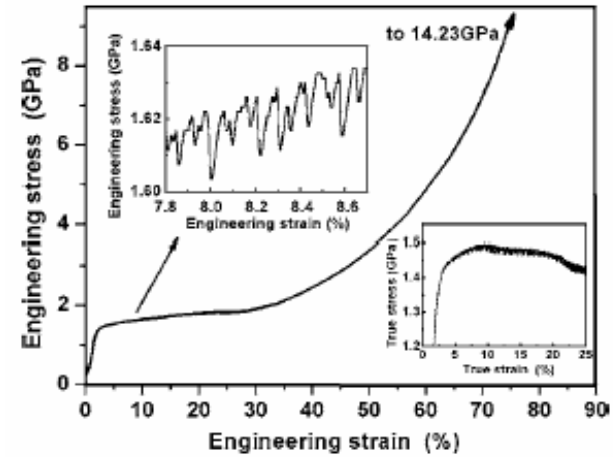
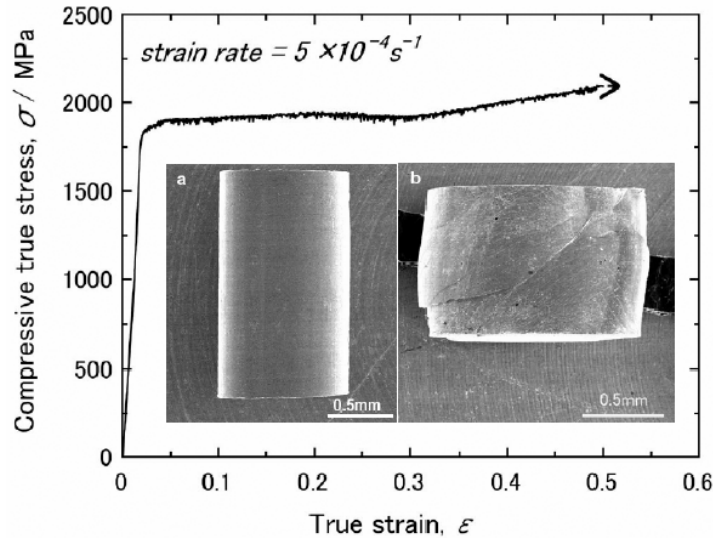
引领出很多大塑性非晶合金新材料

Cu50Zr50

PdSi

CuZrAl

CuZrAlNiSn



$\text{Zr}_{61.7}\text{Al}_8\text{Ni}_{13}\text{Cu}_{17}\text{Sn}_{0.3}$

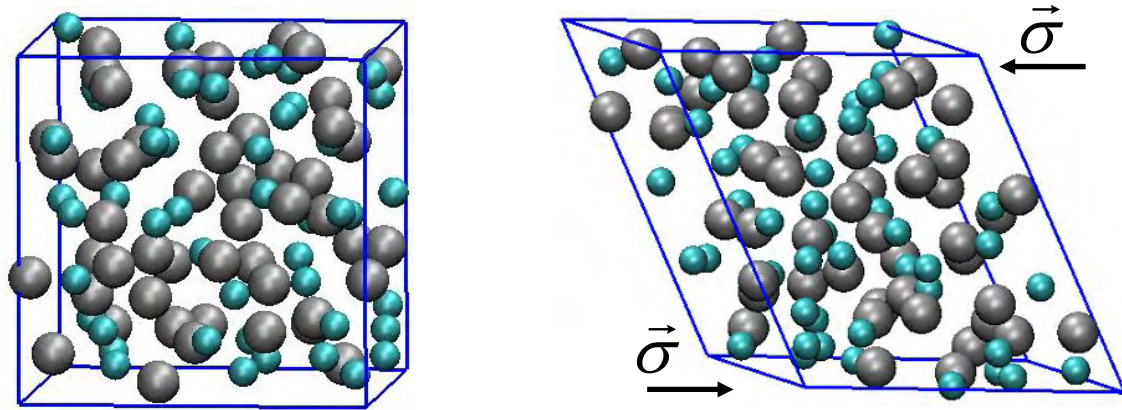


Johnson, Nature, 451, 1085 (2008)

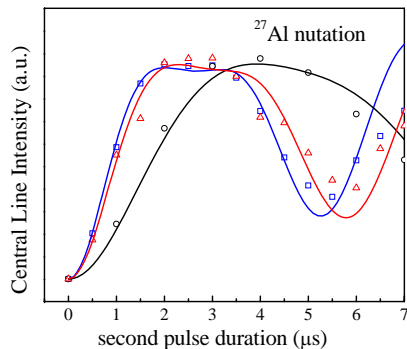
为研究非晶材料的形变机理提供了模型材料

为研究非晶形变提供模型材料

**Metallic glasses with large plasticity
Open a window for understand the intrinsic
mechanism of structural deformation in glass.**



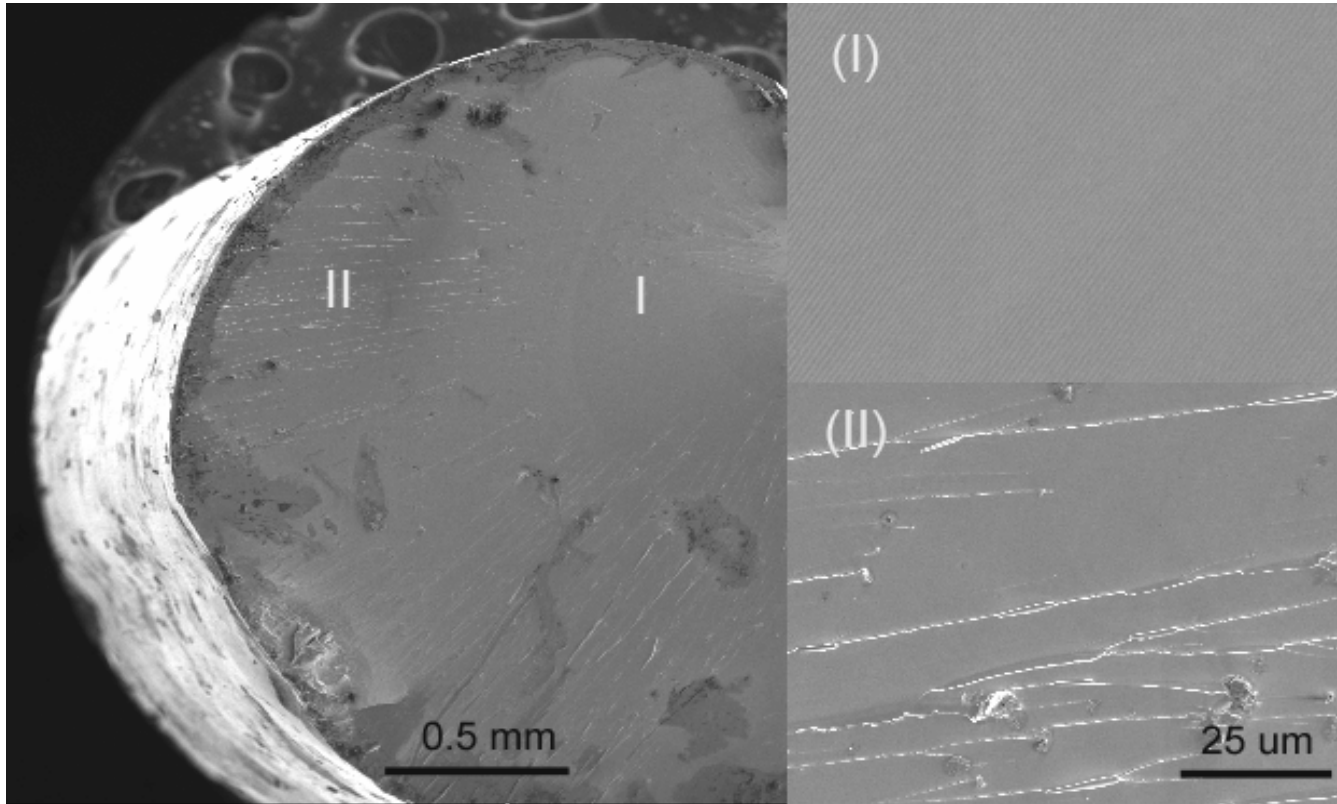
ZrCuNiAl



What is the length scale of plastic deformation?
NMR: local, short range
Neutron: intermediate range
TEM: microstructure

4、非晶研究最其它领域的联系

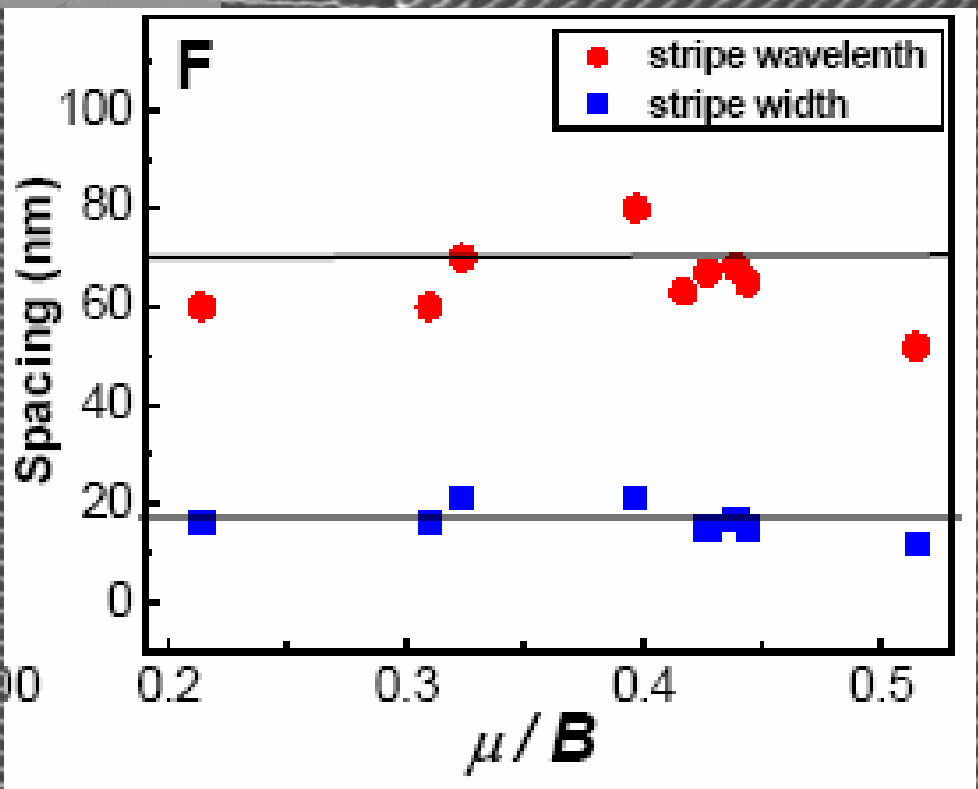
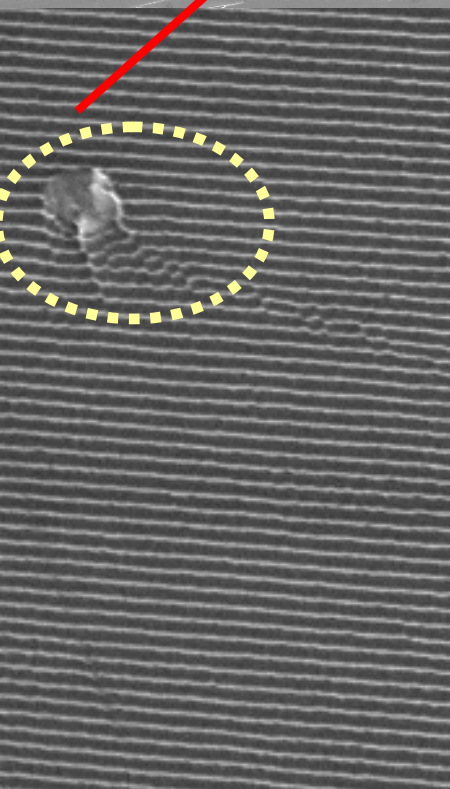
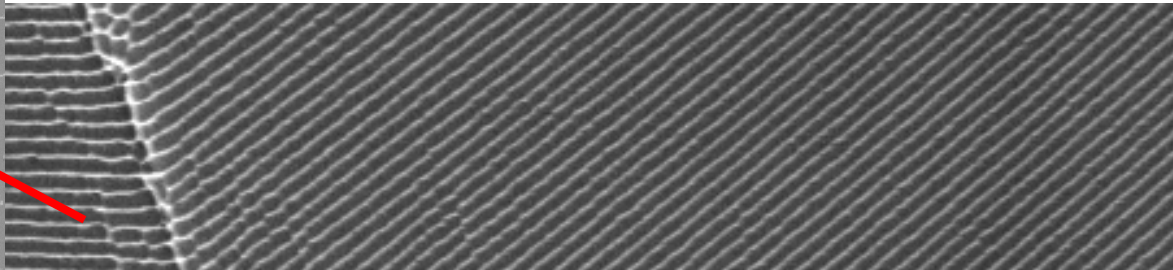
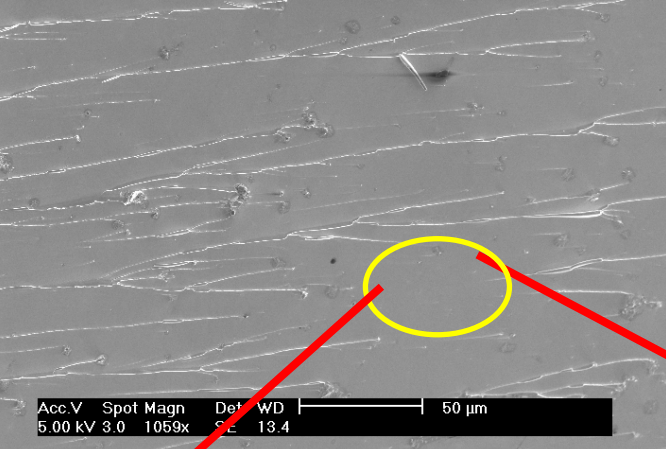
非晶合金断裂面



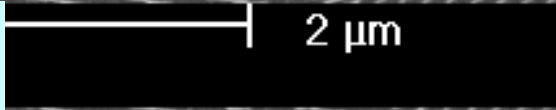
Flat shine fracture surface like silicate glasses

The brittle BMGs close to ideal brittle fracture

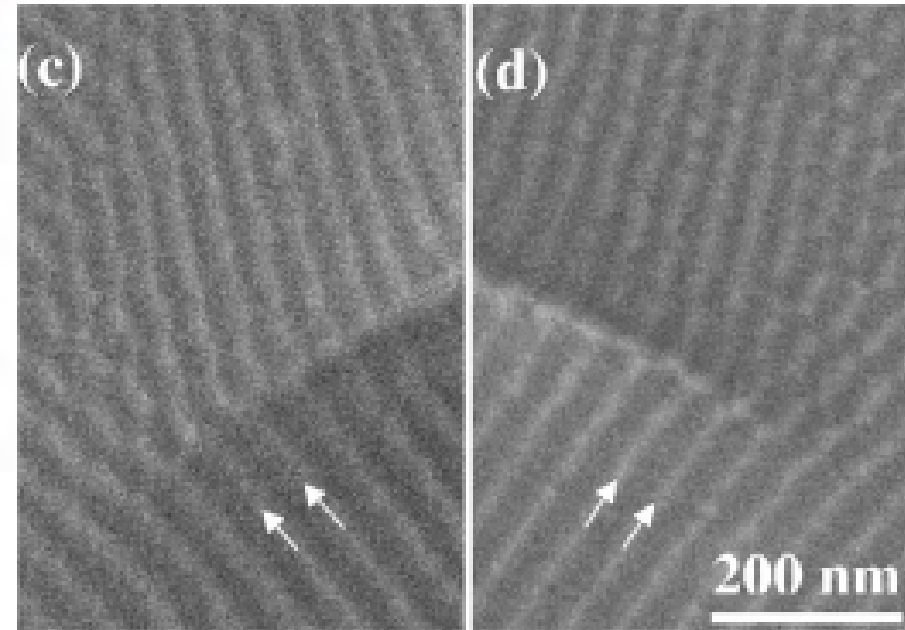
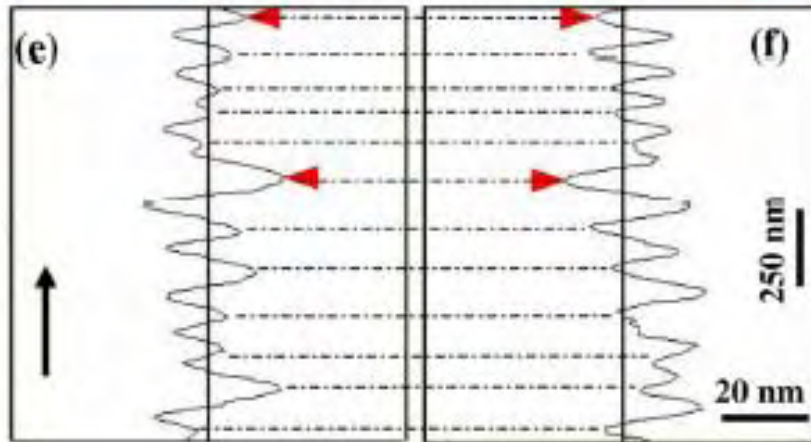
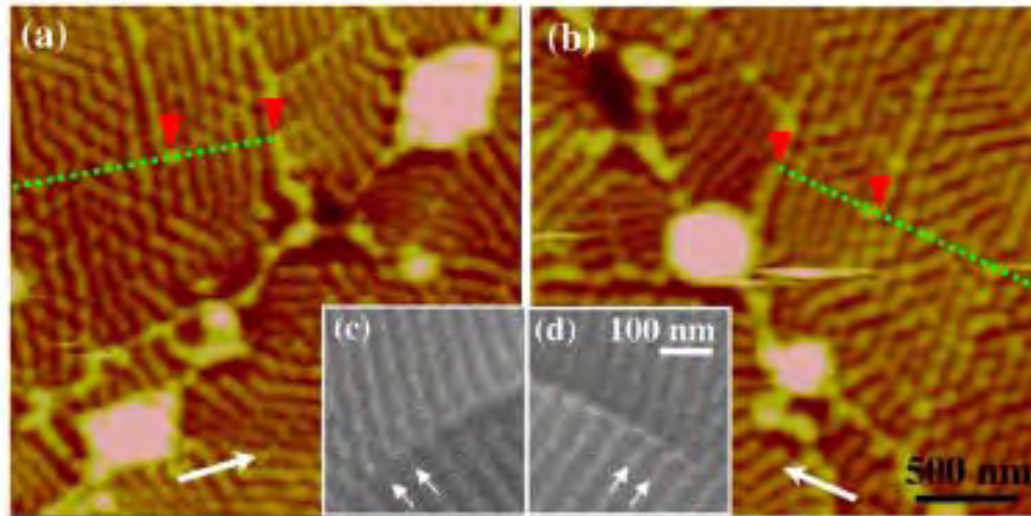
BMG exhibits two distinct zones: flat mirror zone and mist zone consisting of massive river patterns



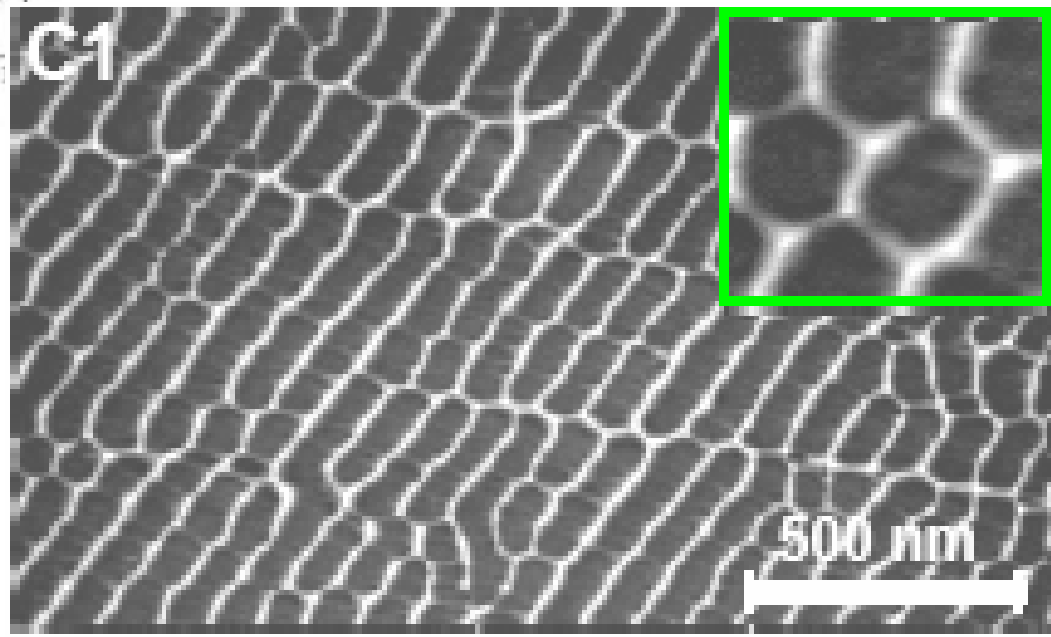
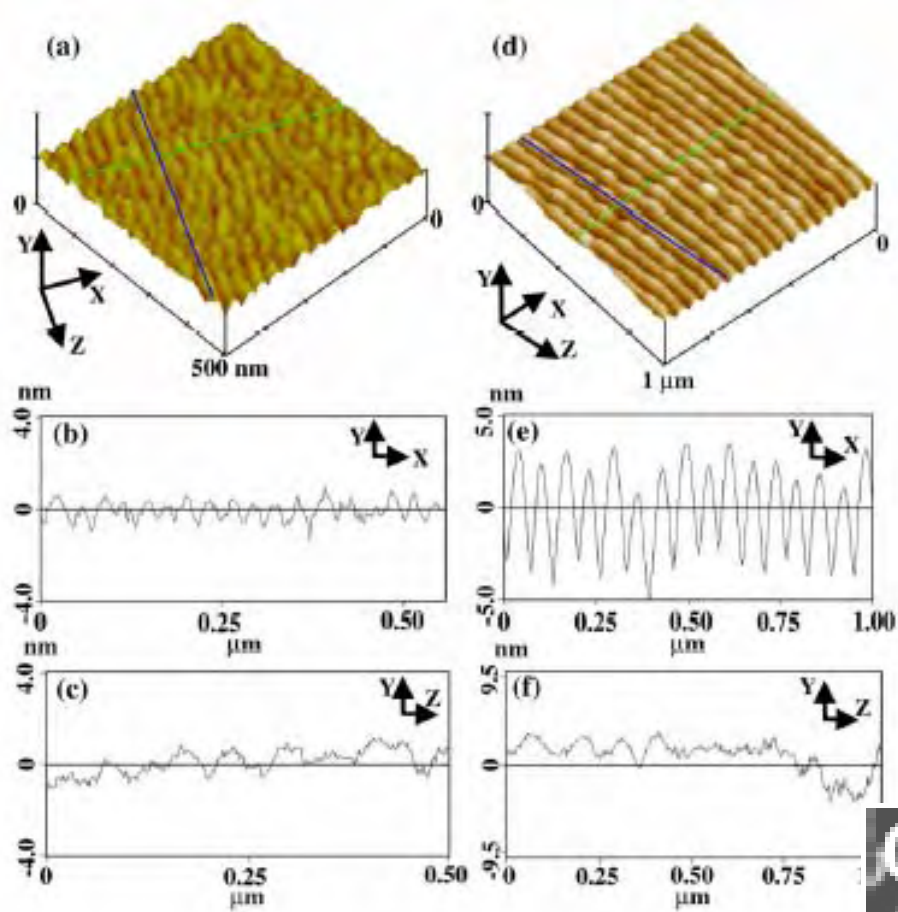
different orientations may coexist



Peak to peak and valley to valley

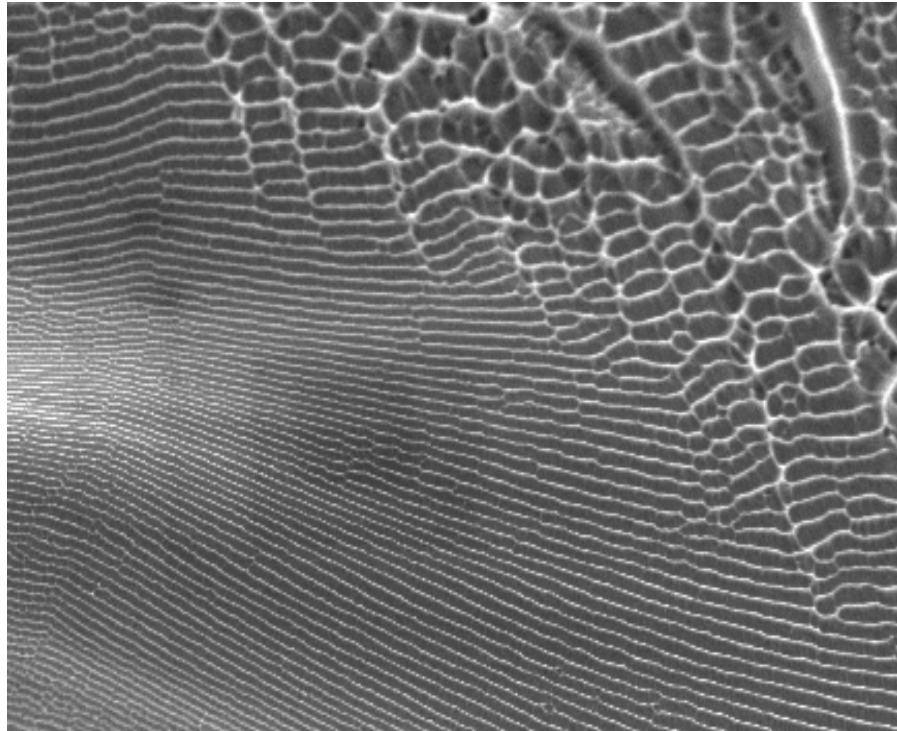
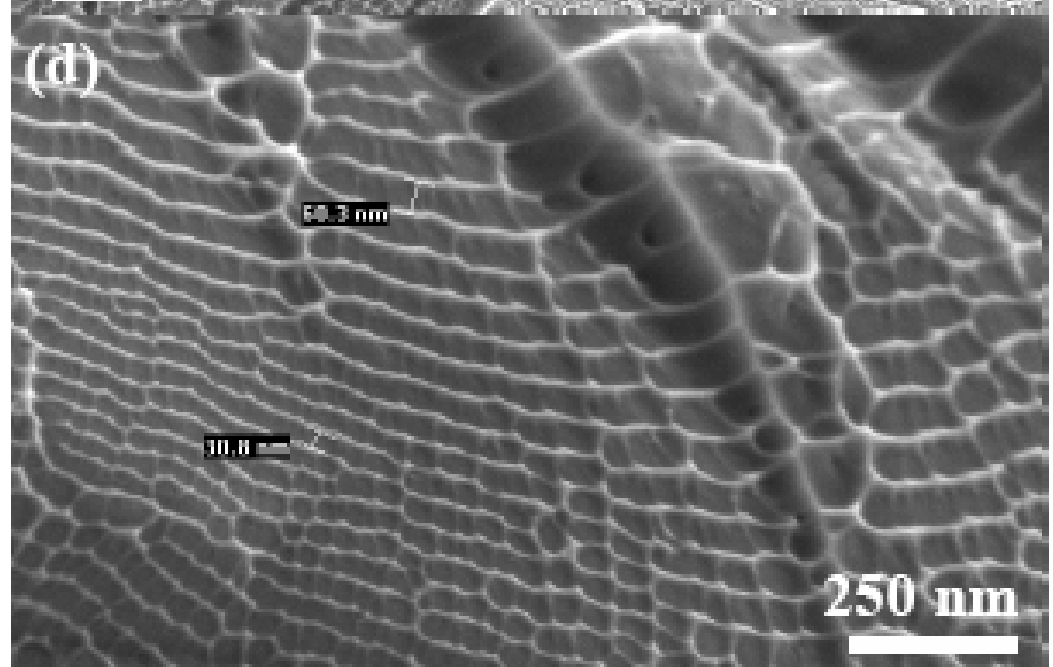


Phys Rev Lett 98, 235501 (2007)



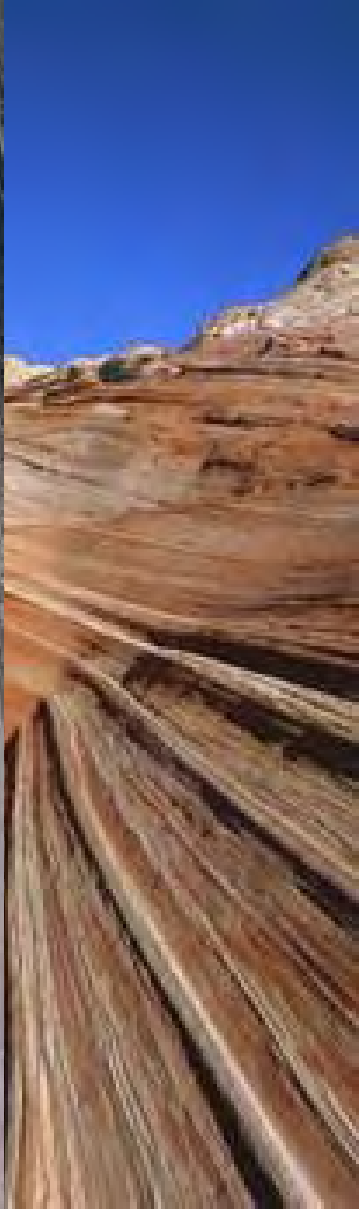
The stripes consist of the hexagonal closed-packing ordered dimples

The transition from dimple to periodic corrugation



a certain dimple density and velocity are required to form a periodic corrugation pattern

APL 89, 121909 (2006)





沙丘上的波纹



指纹

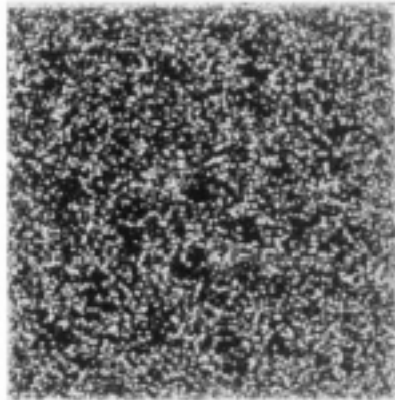
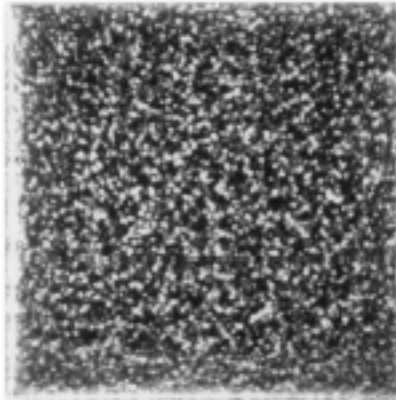
Experiment

Simulation

(e)

$\Gamma=5.00$

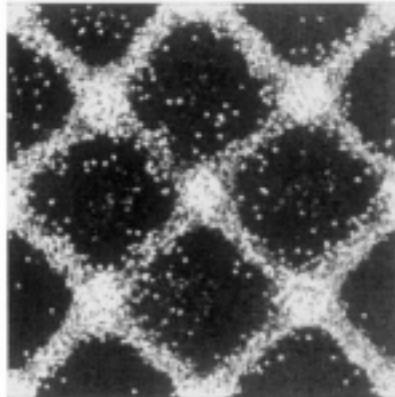
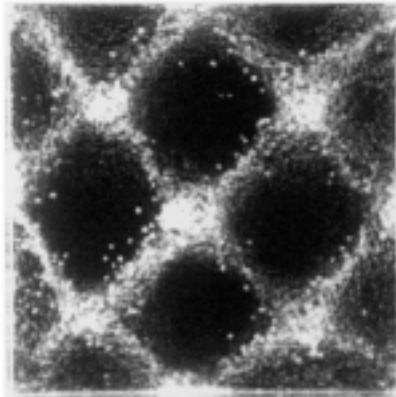
$f^*=0.44$



(f)

$\Gamma=5.79$

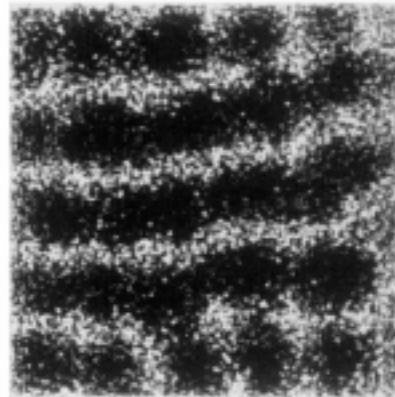
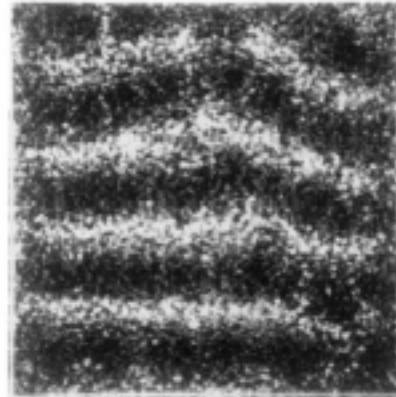
$f^*=0.47$



(g)

$\Gamma=6.00$

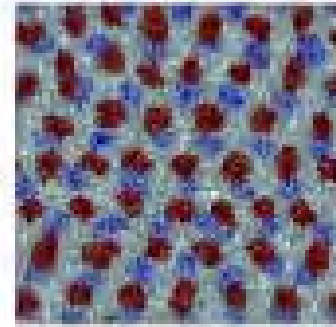
$f^*=0.84$



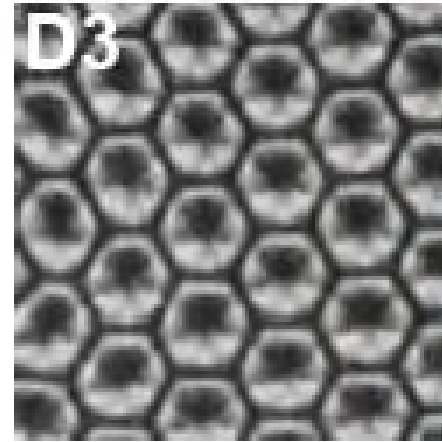
A



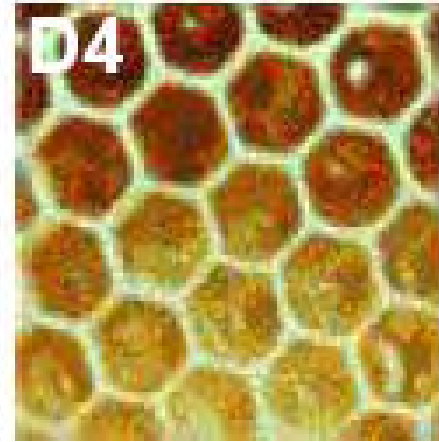
shear



D3



D4



Si oil 表面对流

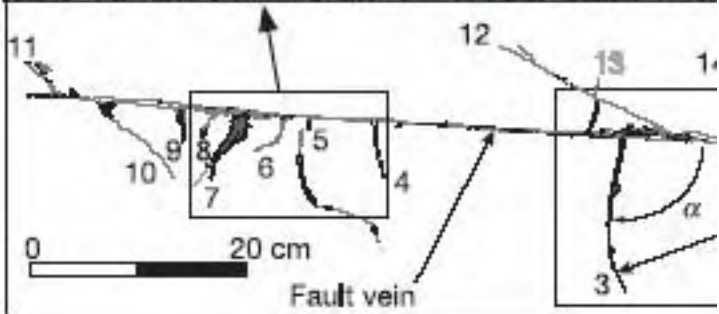
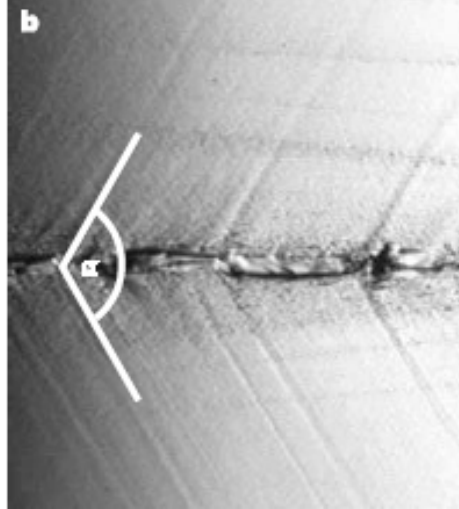
honeycomb

D5

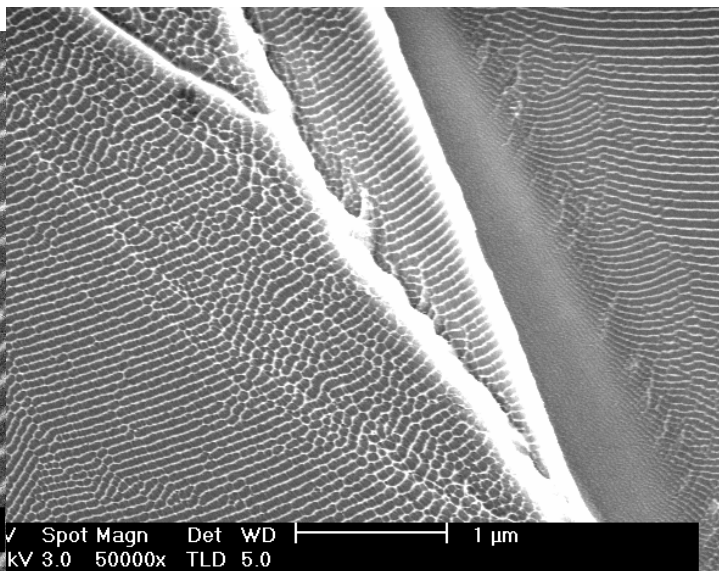
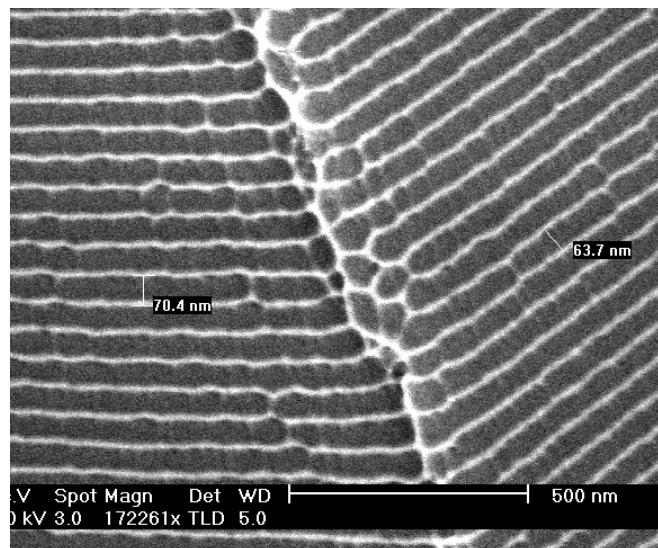
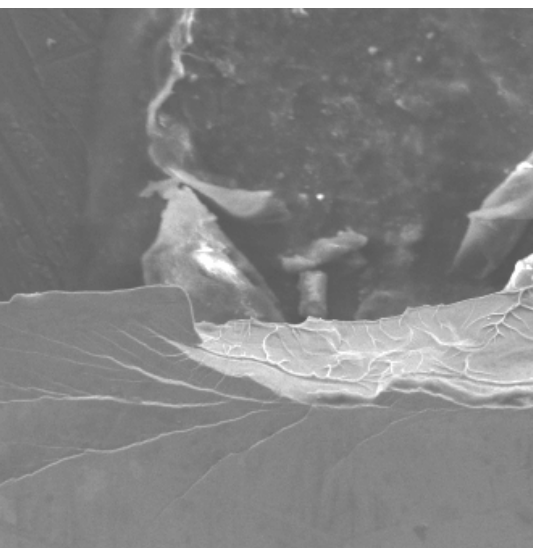


bubble bath

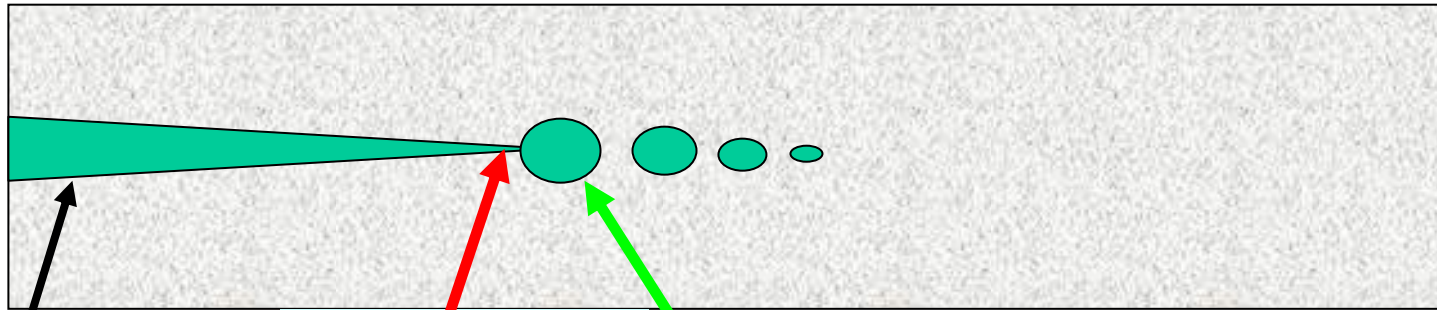
In granular system



Nature 436, 1008 (2005)
Nature 418, 310 (2002)



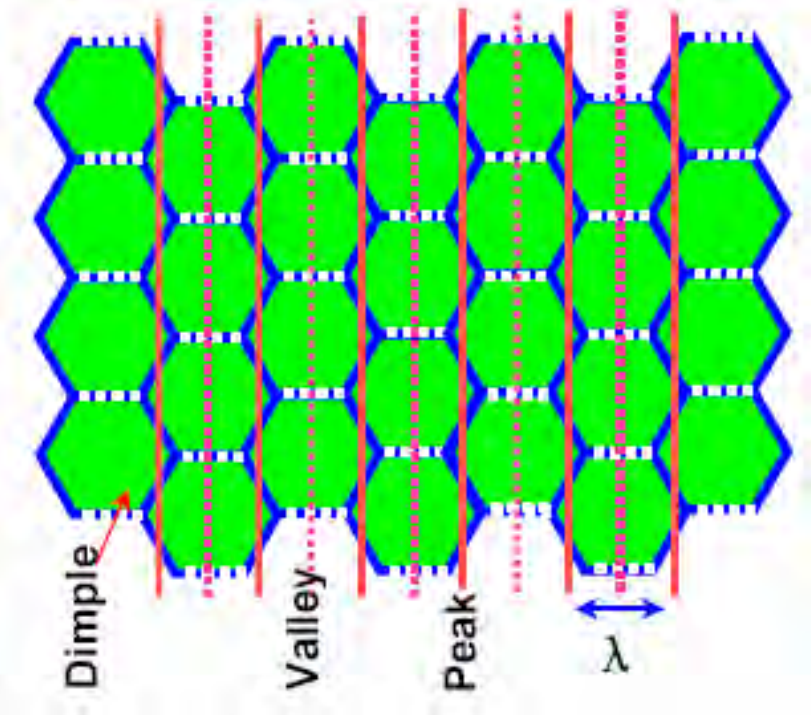
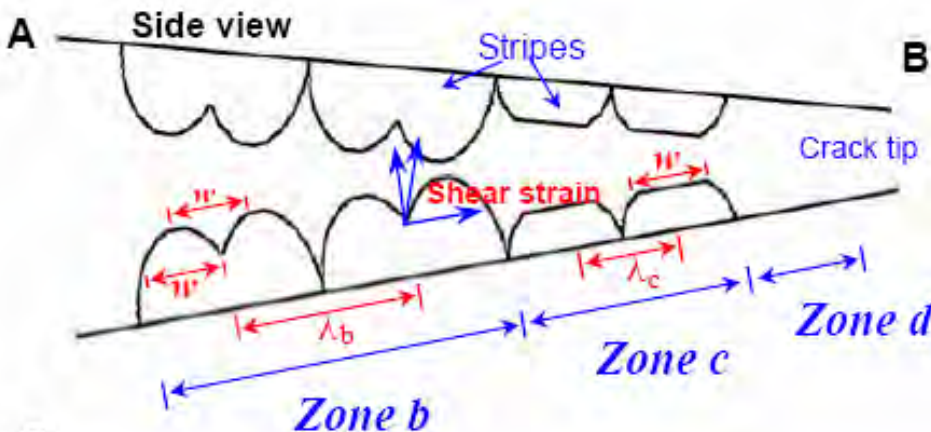
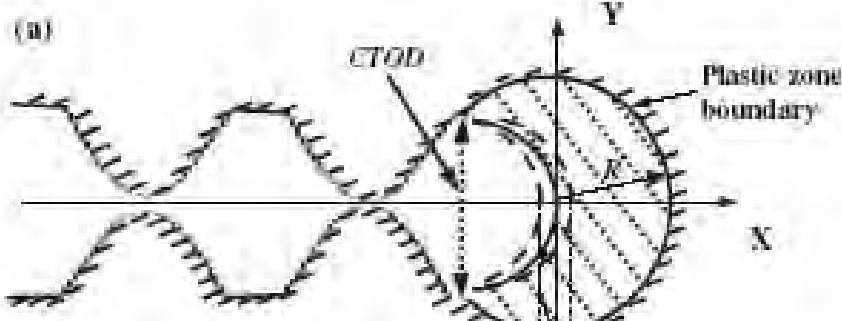
Damage cavities assembly model



crack

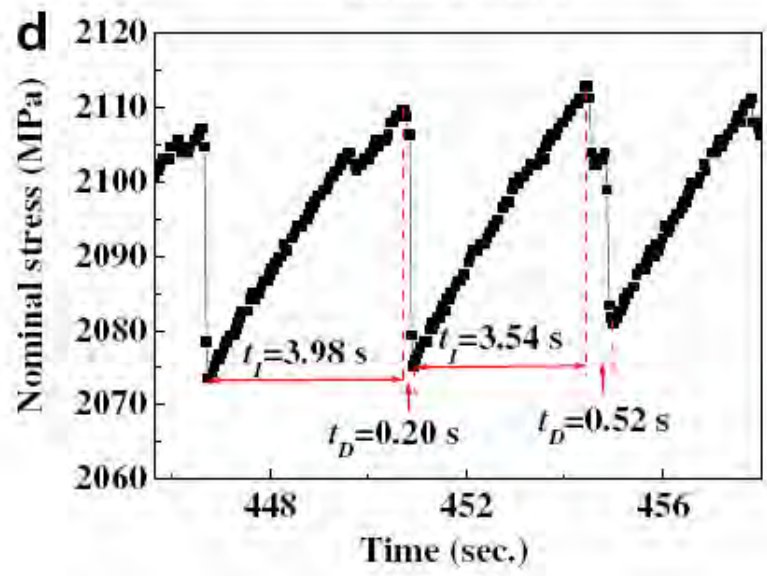
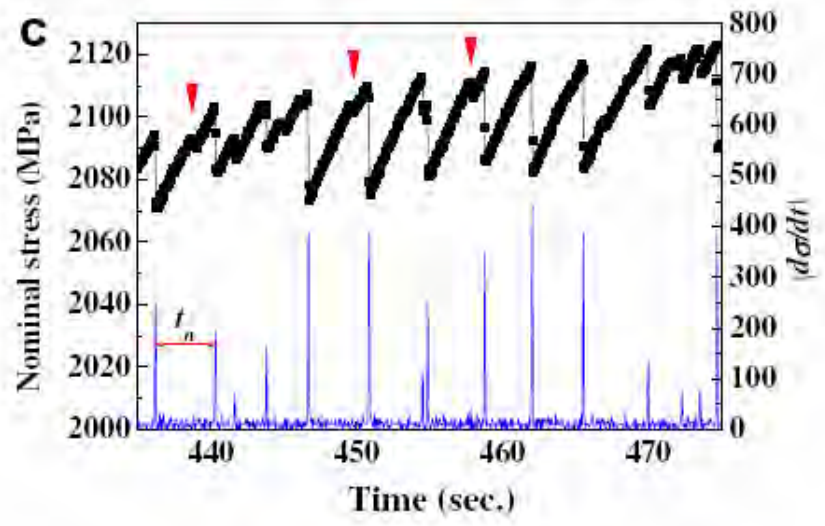
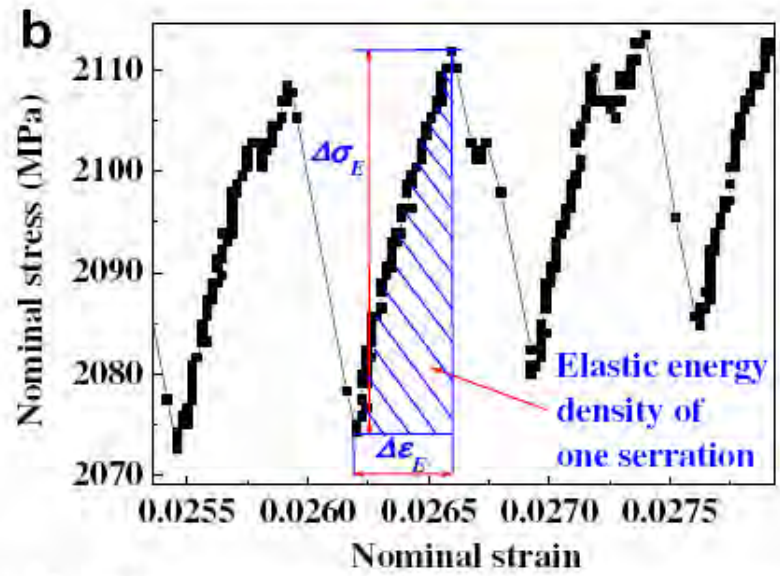
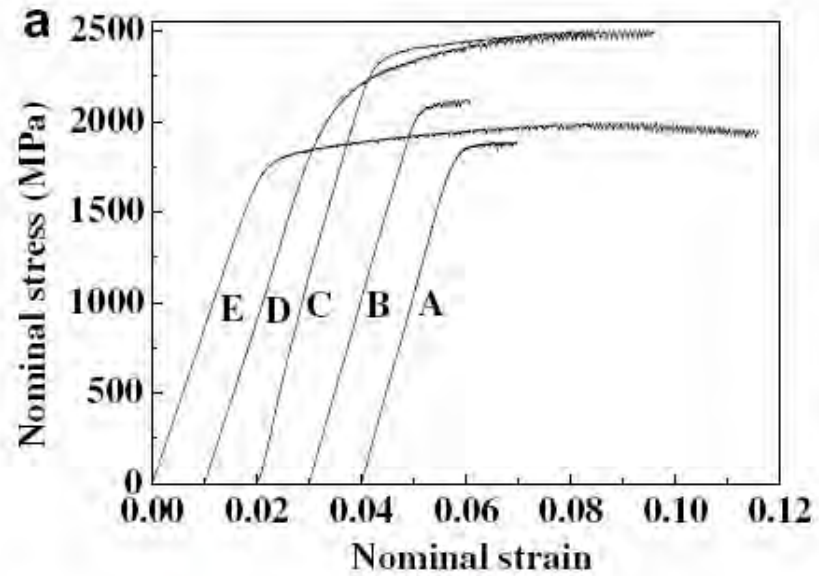
Crack front tip

Plastic zone

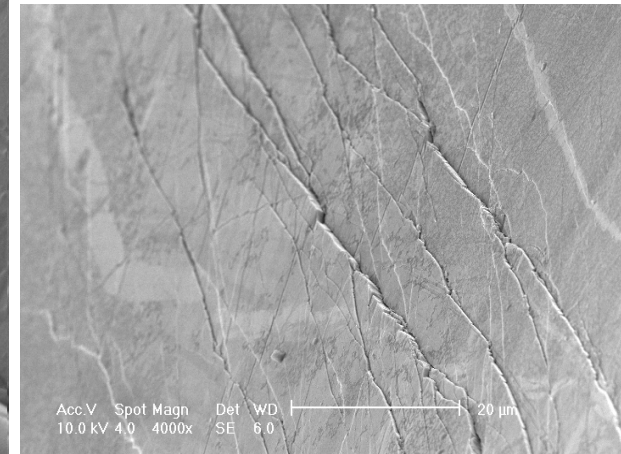
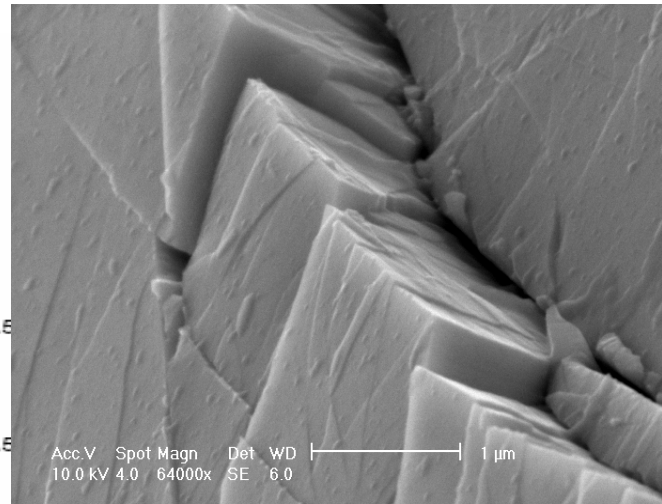
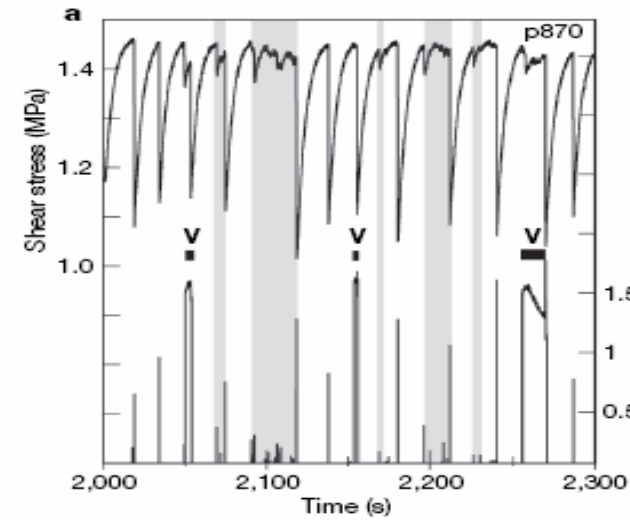
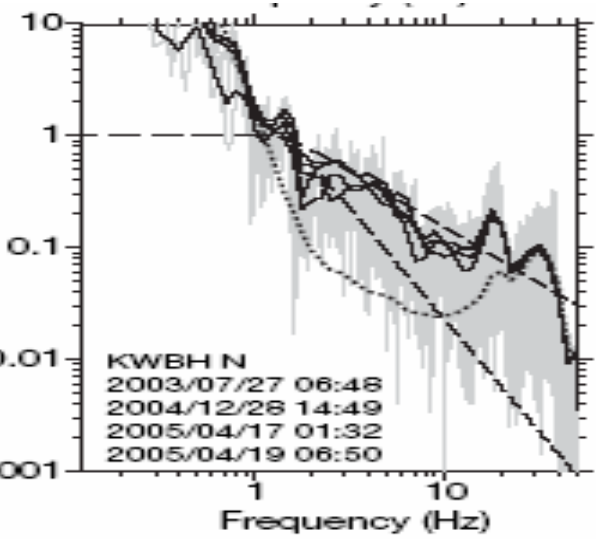


PRL 98, 235501 (2007)

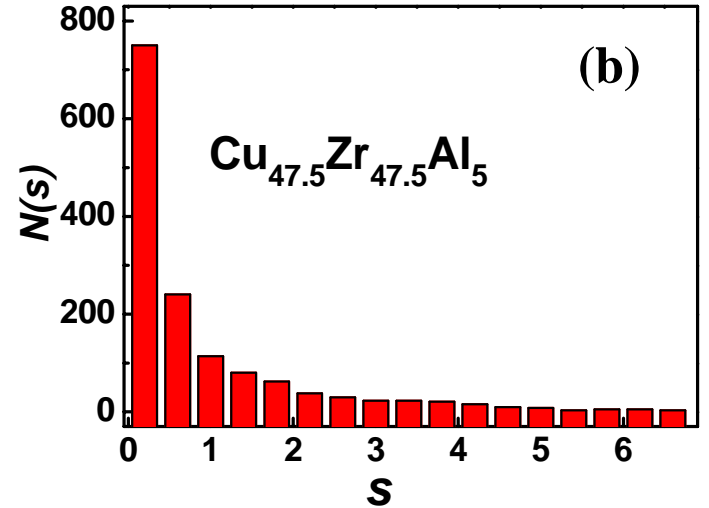
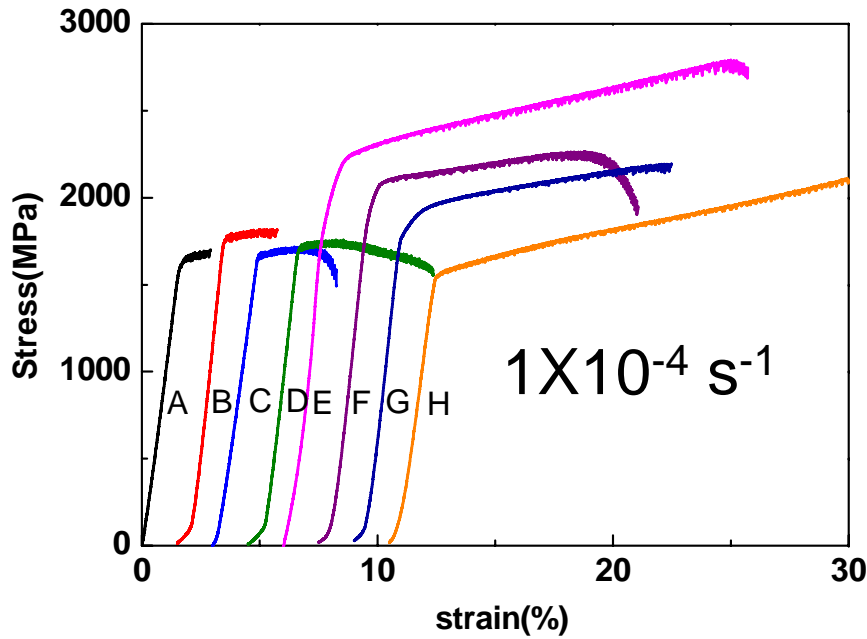
断裂过程中的锯齿波现象



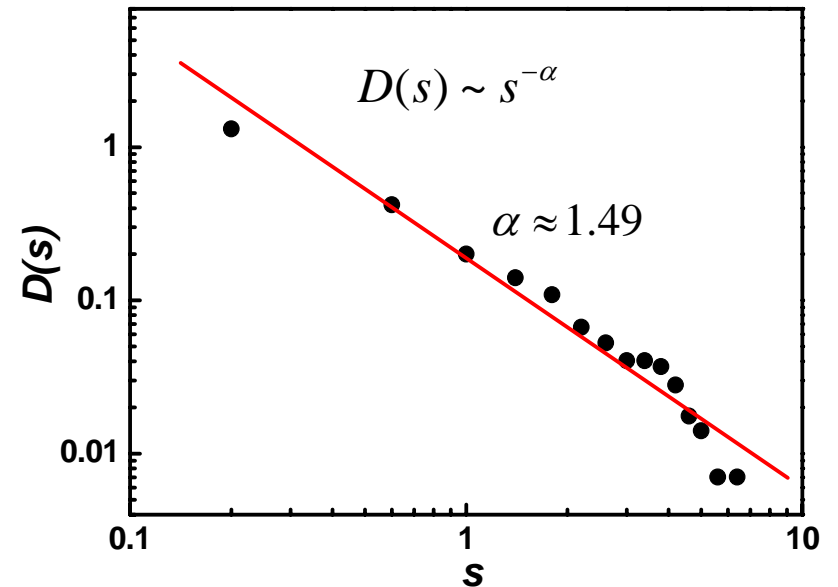
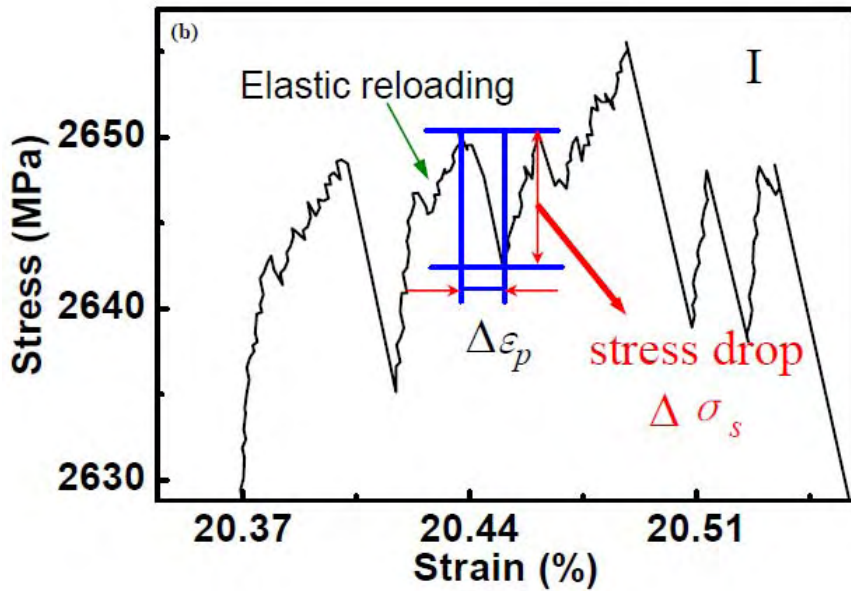
Similar deformation morphology



地震波



A power law distribution

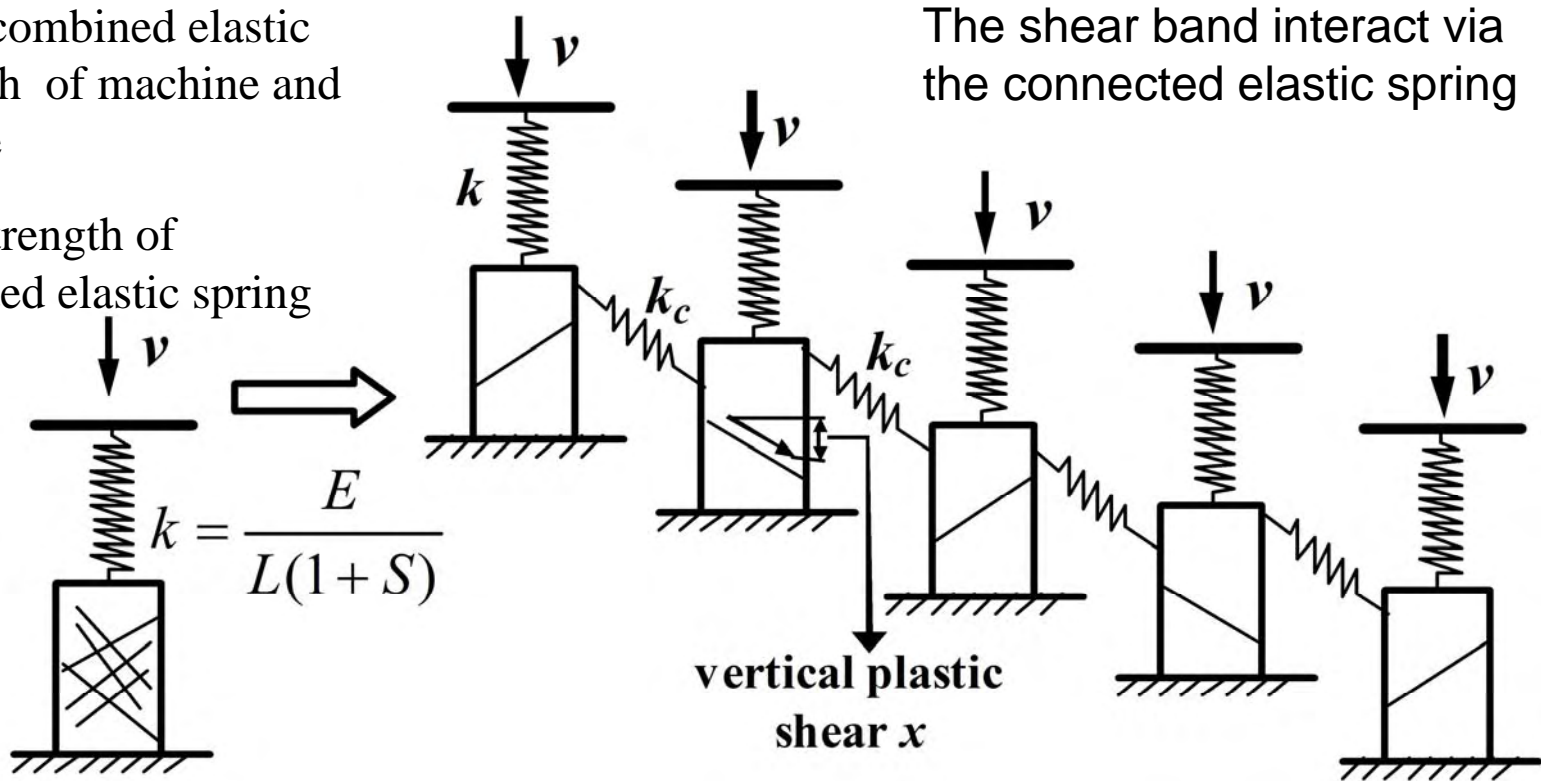


$$D(s) = (1/N)(\delta N(s)/\delta s)$$

Our model considering the interaction of multiple shear bands

k : the combined elastic strength of machine and sample

k_c the strength of connected elastic spring



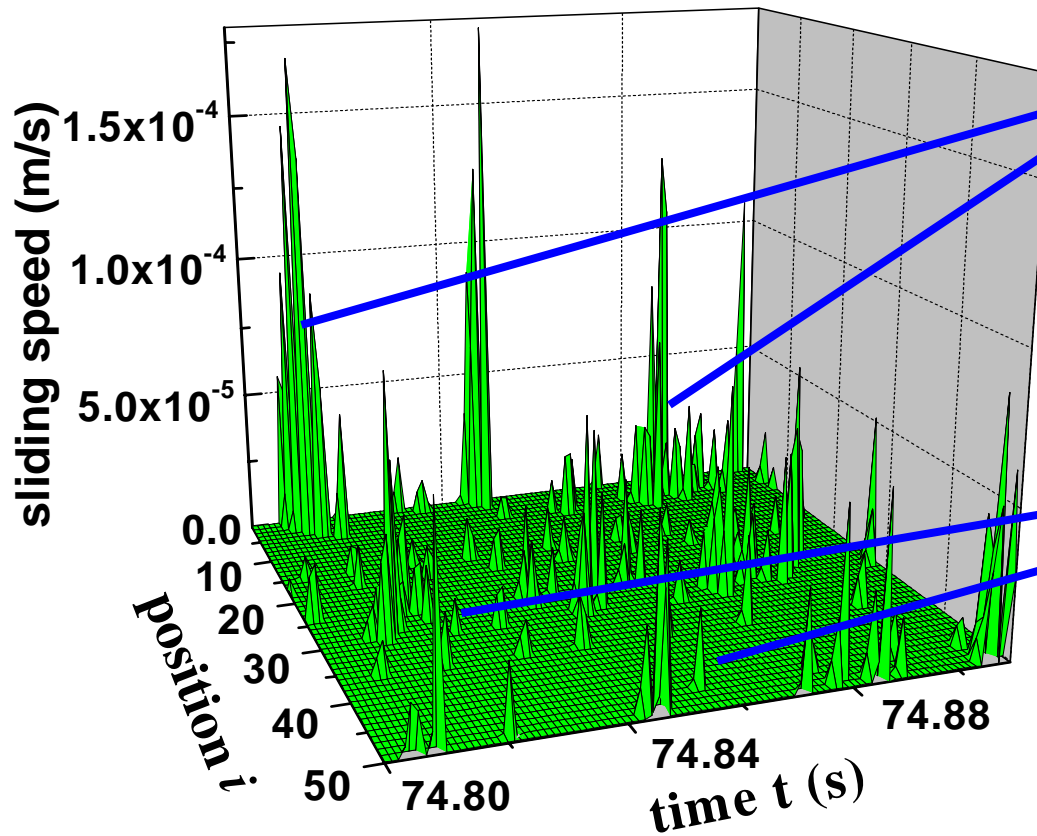
The kinetic equation for the system:

$$[k(vt - x_i) + k_c(x_{i+1} + x_{i-1} - 2x_i) - \sigma_f(\dot{x}_i)] \frac{\pi d^2}{4} = M\ddot{x}_i$$

$$\sigma(x) = \sigma_{ys} - E \frac{x_s}{L} = \sigma_{ys} - \frac{E}{L} \frac{\kappa_M}{(\kappa_S + \kappa_M)} x = \sigma_{ys} - \frac{Ex}{L(1+S)}$$

Shear resistance of material

Numerical solutions: The shear-band sliding events display various size and occur intermittently, and time-spatial coupled



Large events involving a large number of shear band sliding

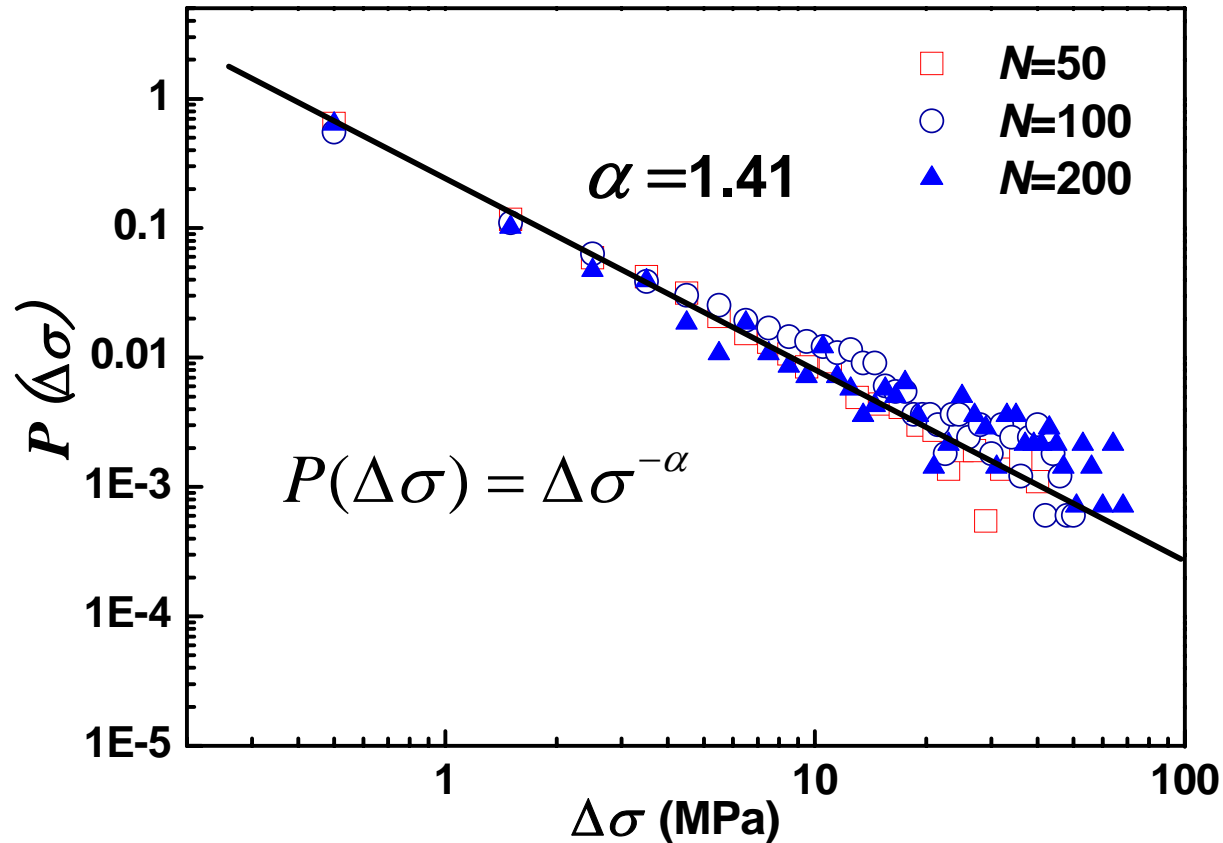
Small events involving only one or a few shear band sliding

Event involving all blocks can also be observed, though very rare, corresponding the failure of the sample.

$$k_c = 0.8k, N = 50$$

The plastic shear of ductile BMG is very similar to the earthquake behavior!

The calculated stress drop probability distribution can be well fitted by a power law distribution, reproduce the experimental observation



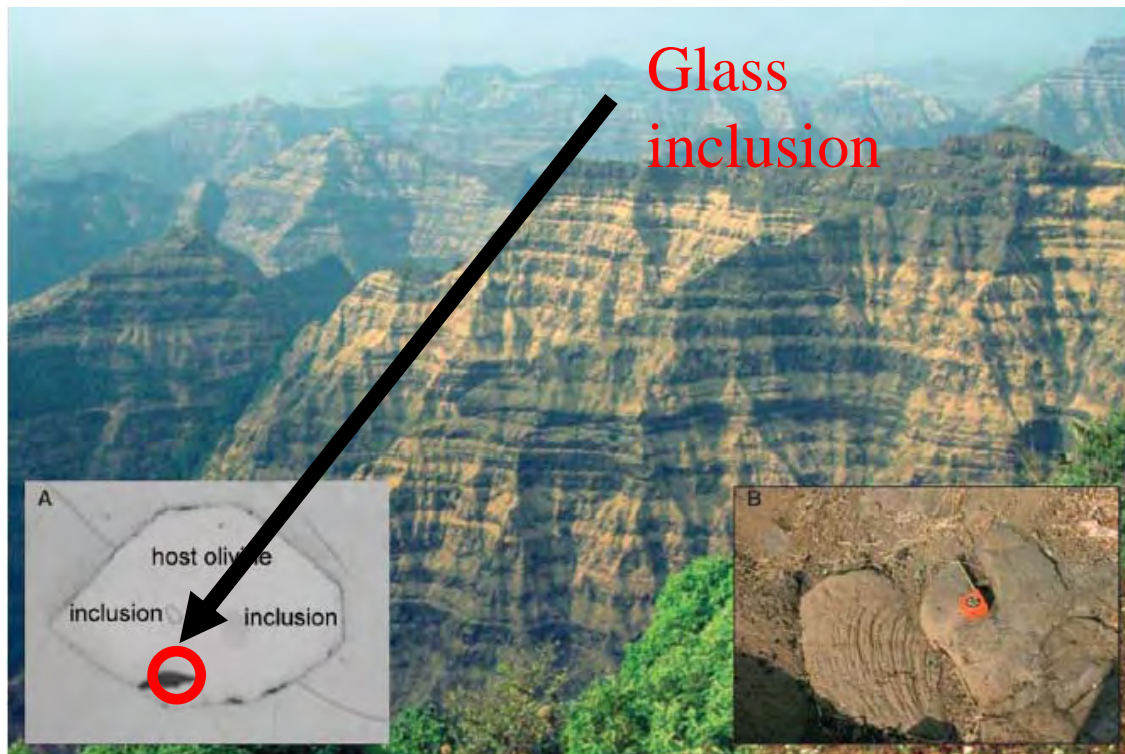
PRL 105 (2010) 035501



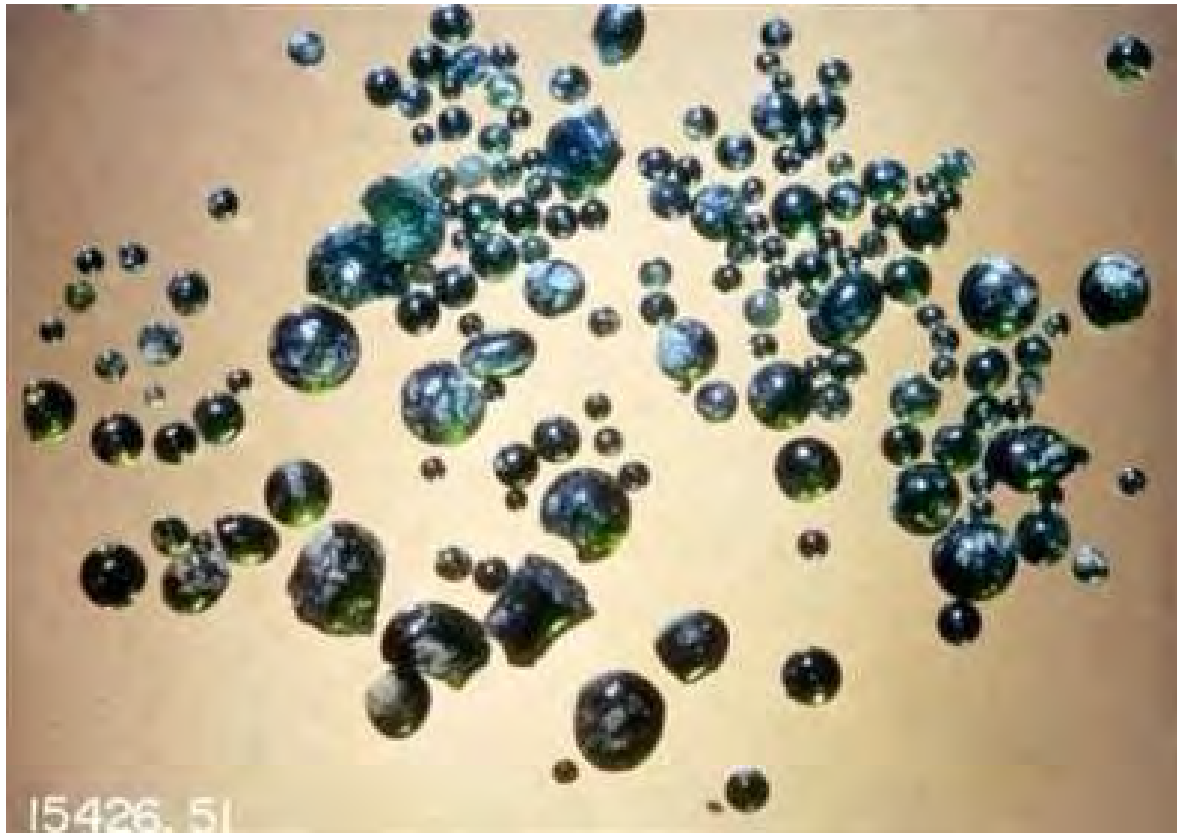
Science 319, 1655 (2008)

恐龙曾统治地球长达数千万年，但在6500万年前突然灭绝！

德干火山岩(即玄武岩)中发掘出玻璃的痕迹，这使得英国研究小组能够对最初的气体成分进行分析。火山喷发中喷涌到大气中的硫，Cl，导致了大范围的物种包括恐龙灭绝



通过对月球火山玻璃球研究显示月球曾有水



*Nature*454, 192 (2008)

The volatile budget of the lunar mantle can, at present, only be reconstructed from the record preserved in the mare basalts and the lunar volcanic glasses, the most primitive basalts from the Moon.

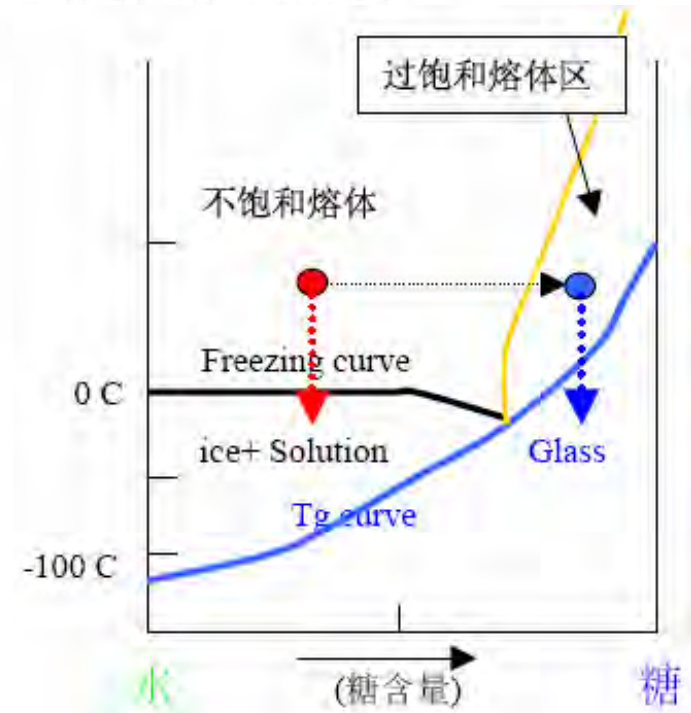


Northern Wood Frog

Rana sylvatica

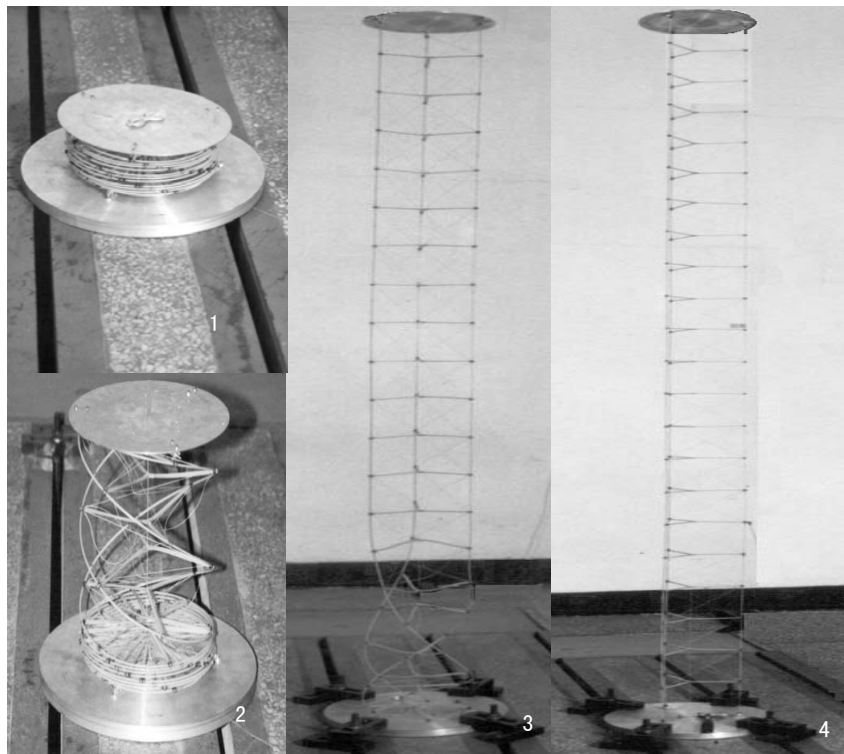
— the only frog found north of the Arctic circle

— when frozen, the frog's breathing, blood flow and heartbeat stop

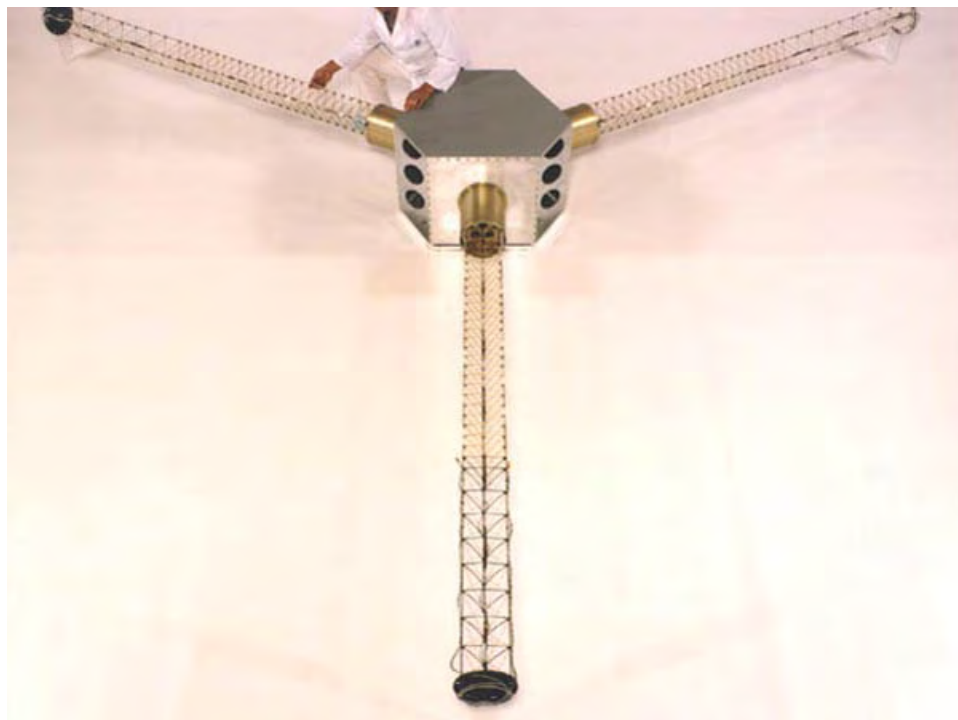


四、应用

利用非晶合金高比强度、大弹性变形 ($\sim 2\%$)、低热膨胀系数等特性



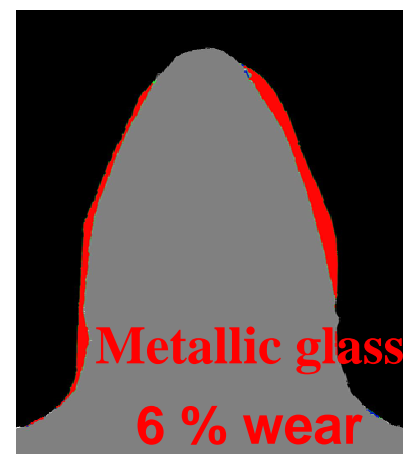
盘压杆



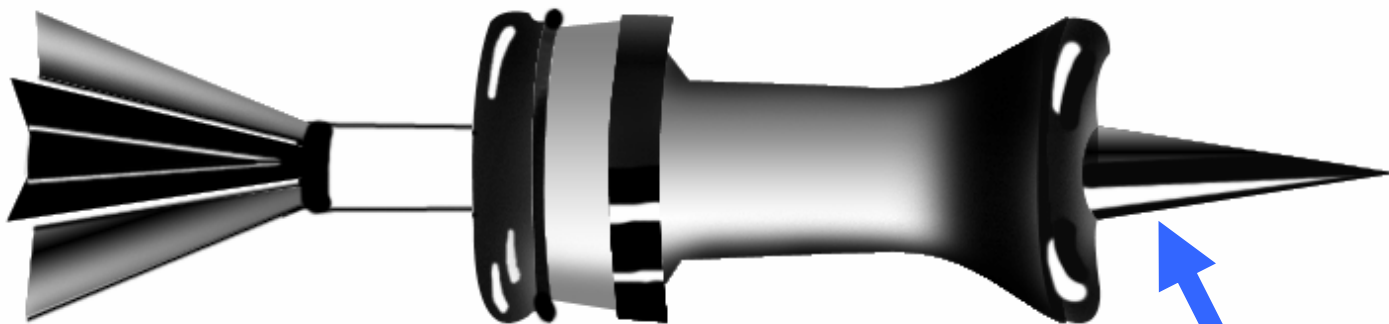
卫星探测器撑杆

卫星重要结构部件

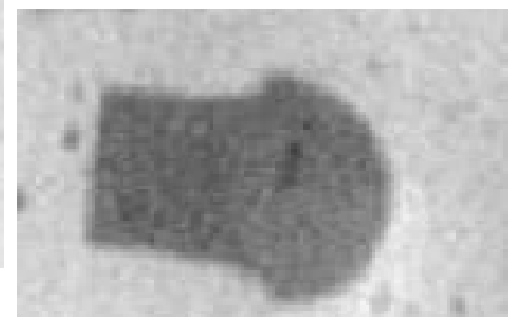
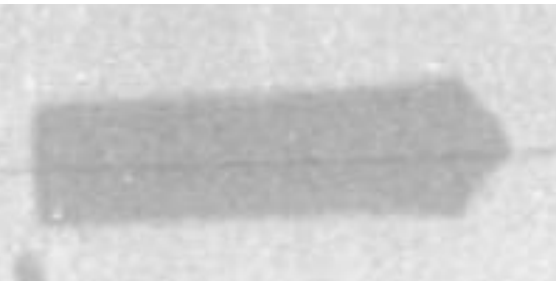
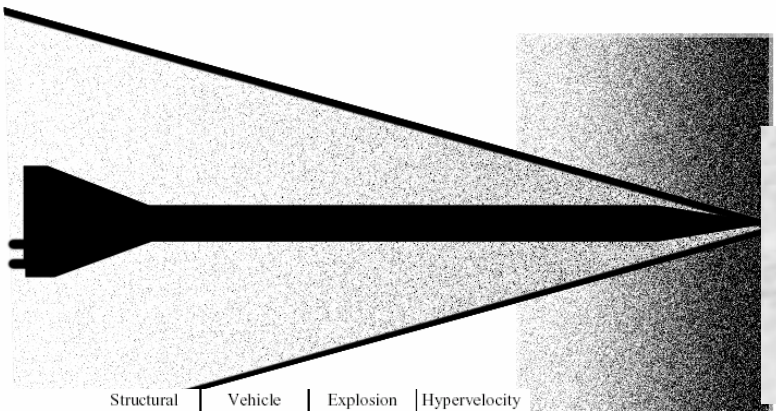
空间活动部件用齿轮



大块非晶合金穿甲弹

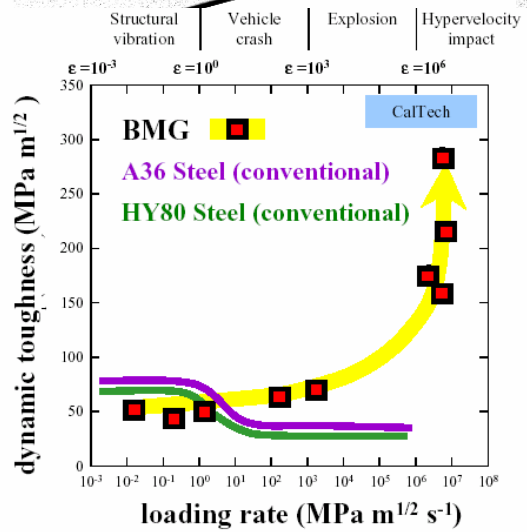


大块非晶



W alloy

高动态断裂韧性及自锐性



CalTech



谢谢！