无网格法

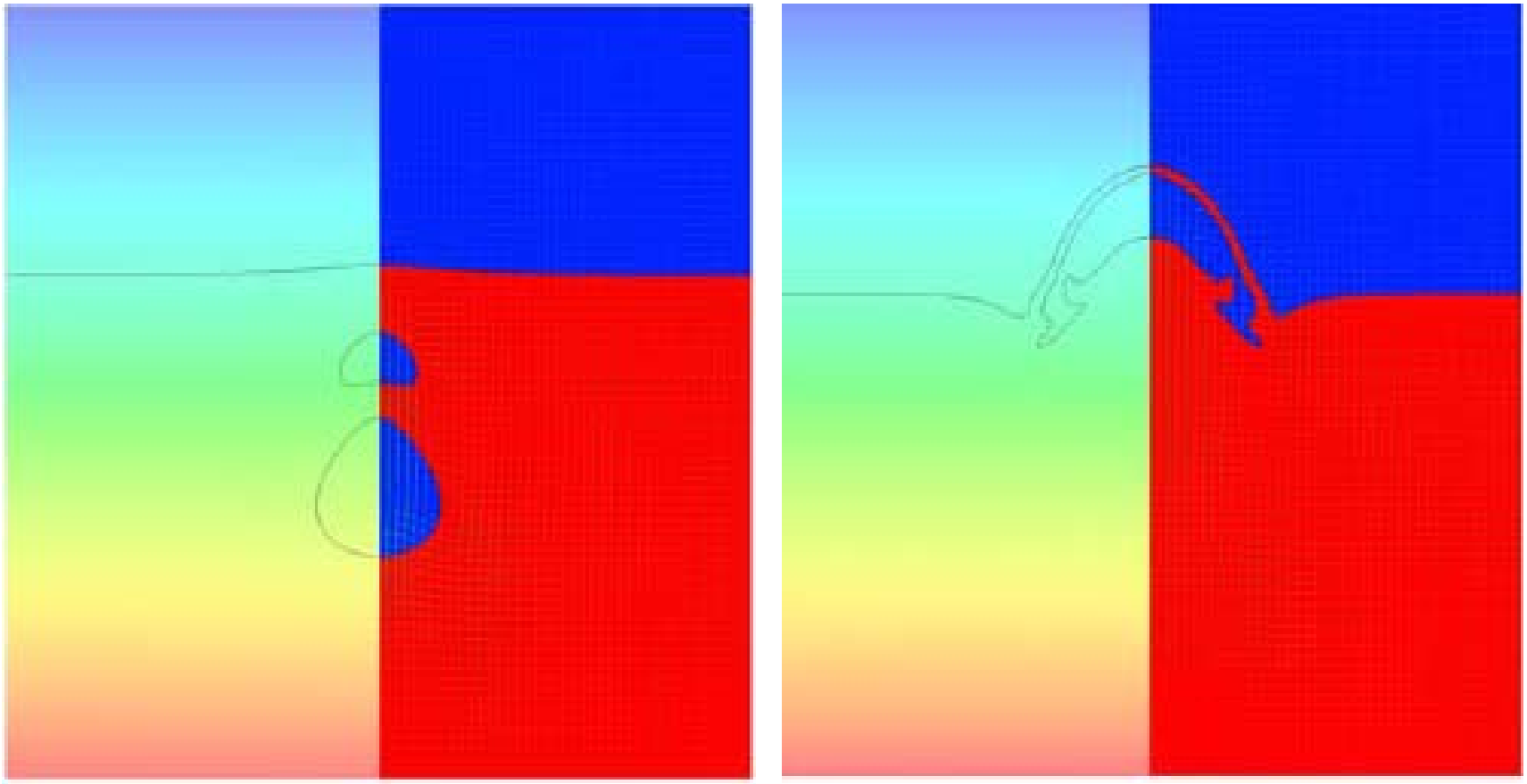
典型无网格法



无网格法的应用

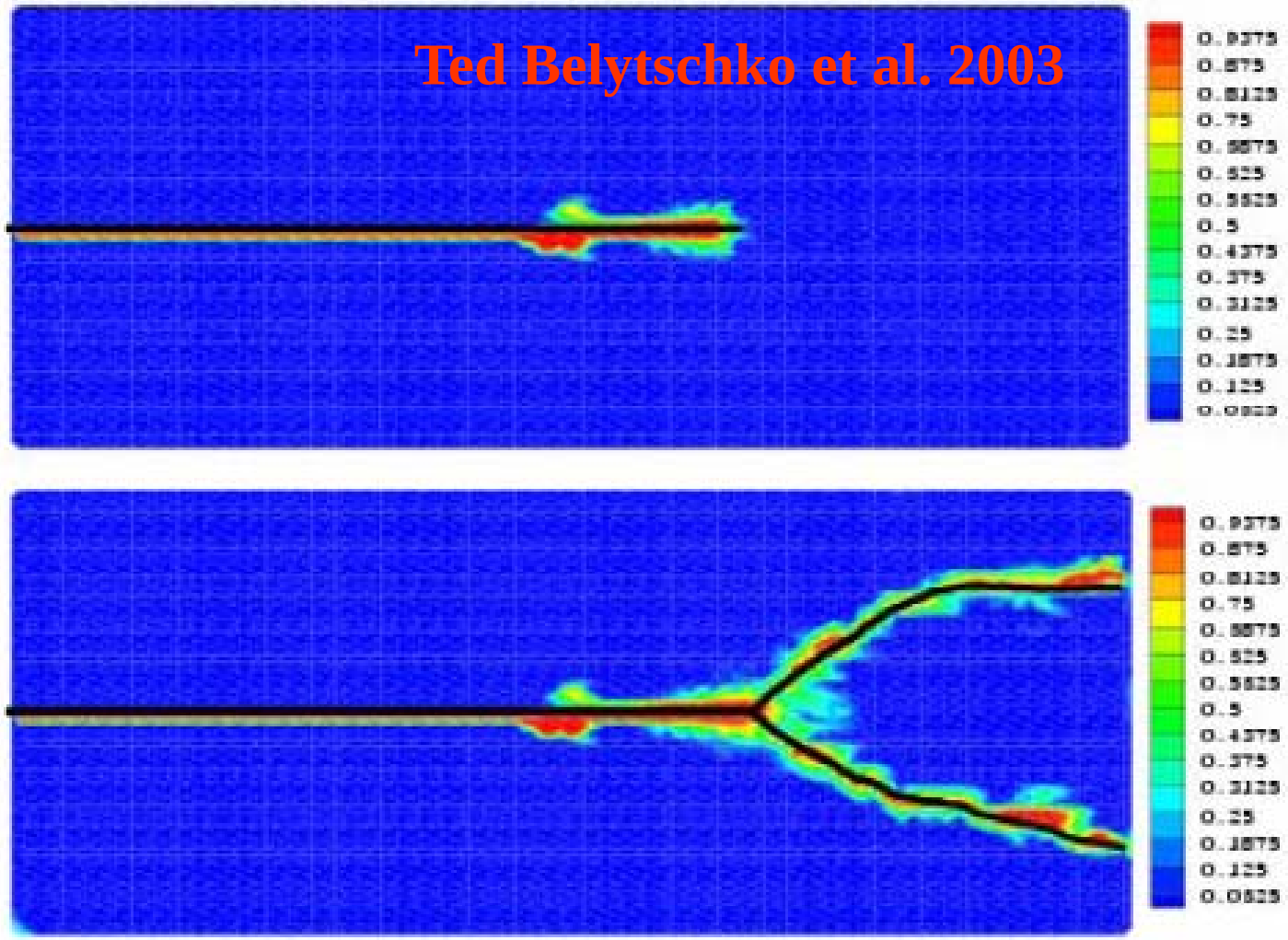
- 天体物理
- 水下爆炸
- 高速碰撞
- 动态裂纹扩展
- 板壳分析
- 流体力学
- 相变问题
- 大变形
- 自适应
- 金属加工成型
- 塑性变形局部化
- 纳米管起皱

无网格法的应用

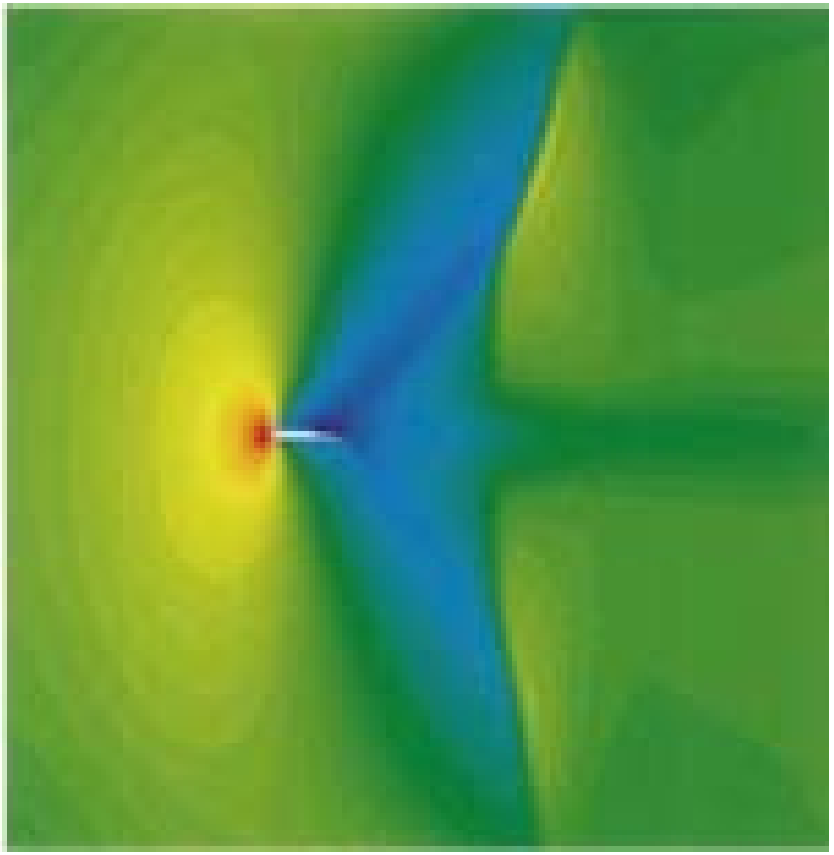


Ted Belytschko et al. 2003

无网格法的应用



无网格法的应用





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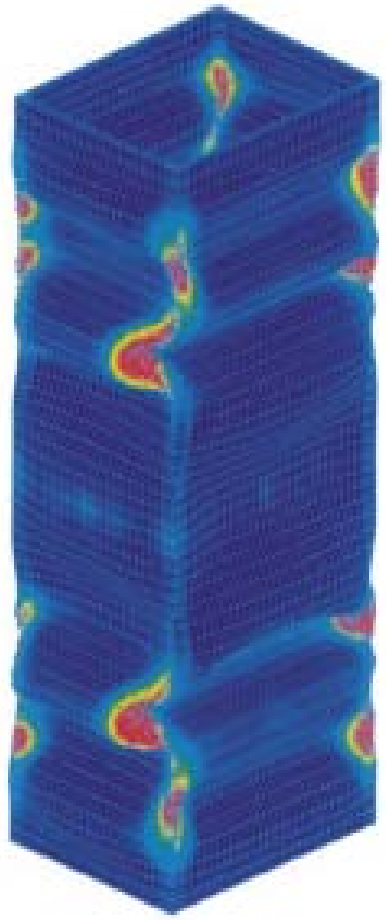

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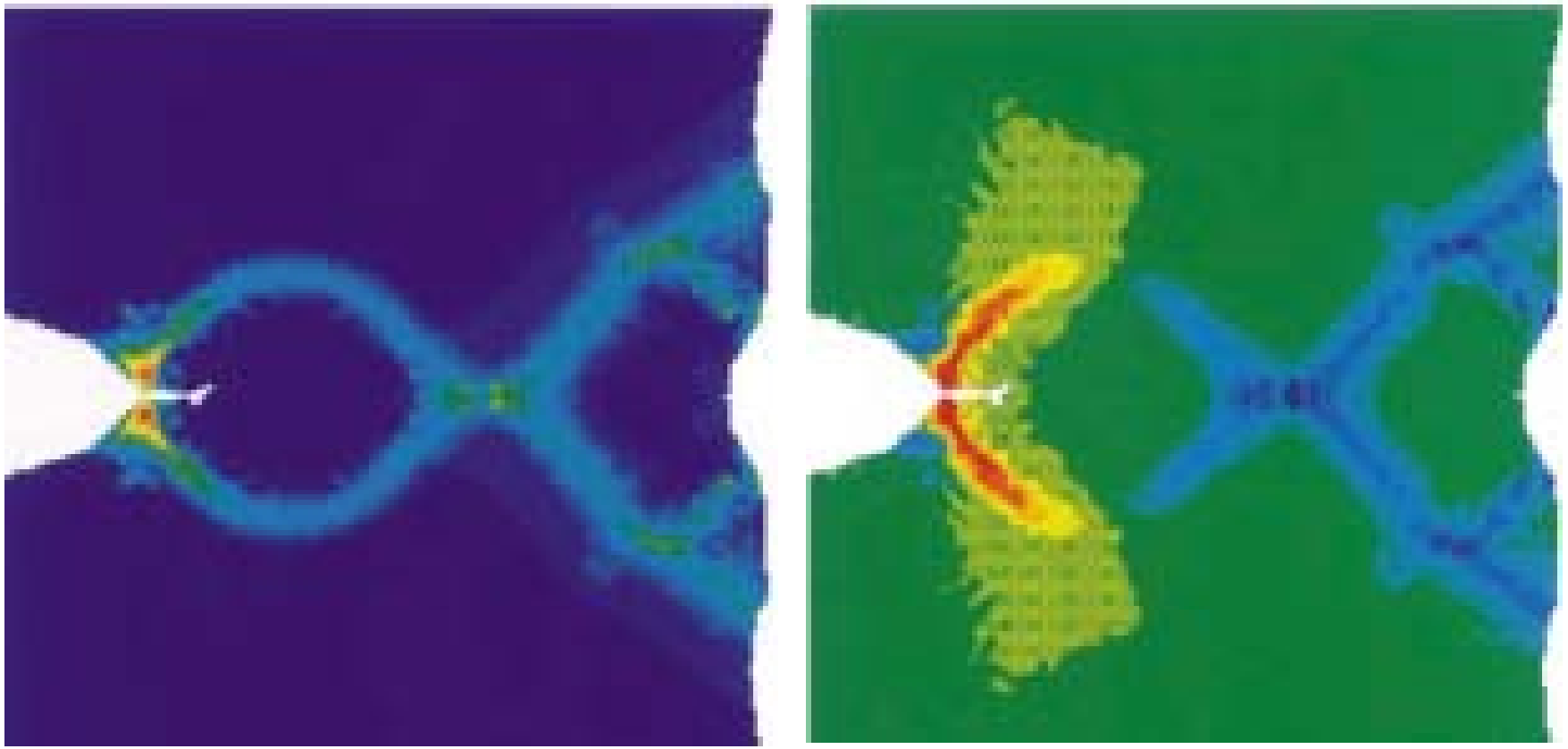

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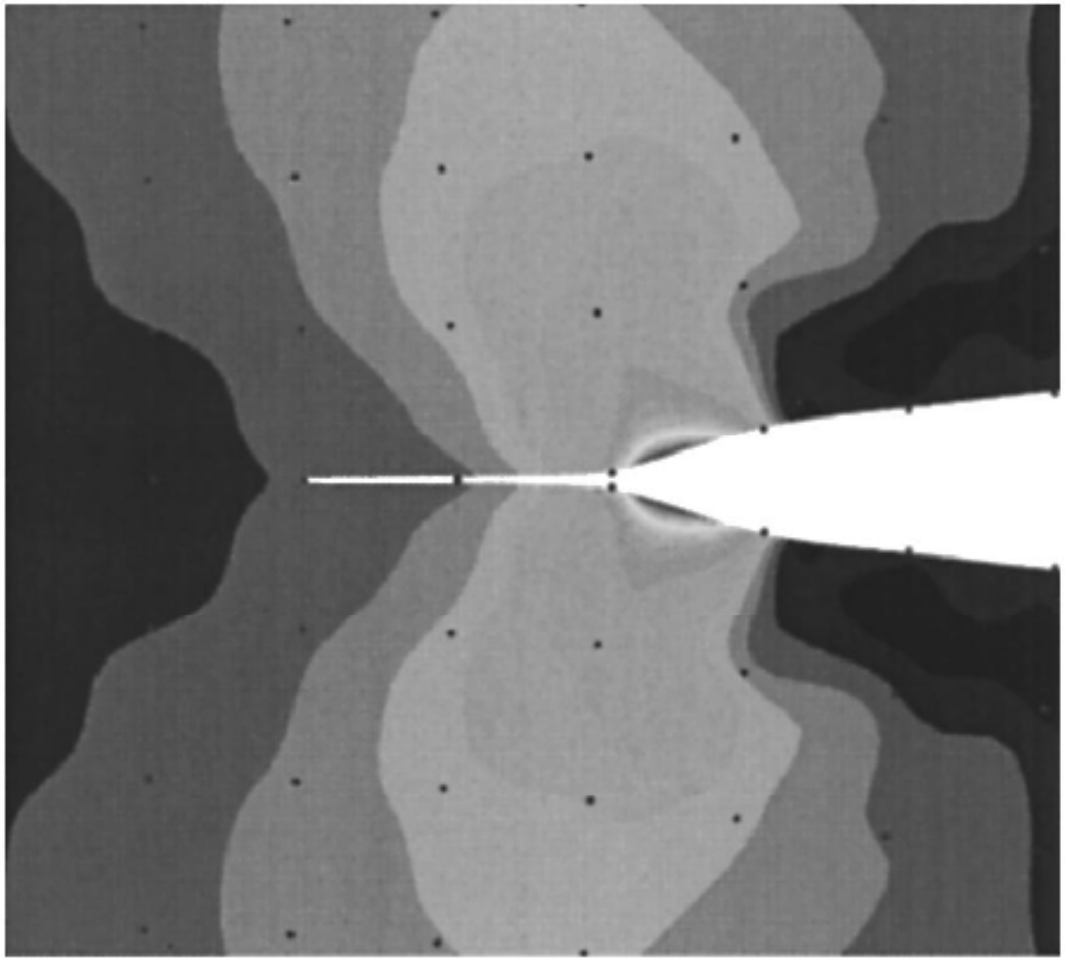
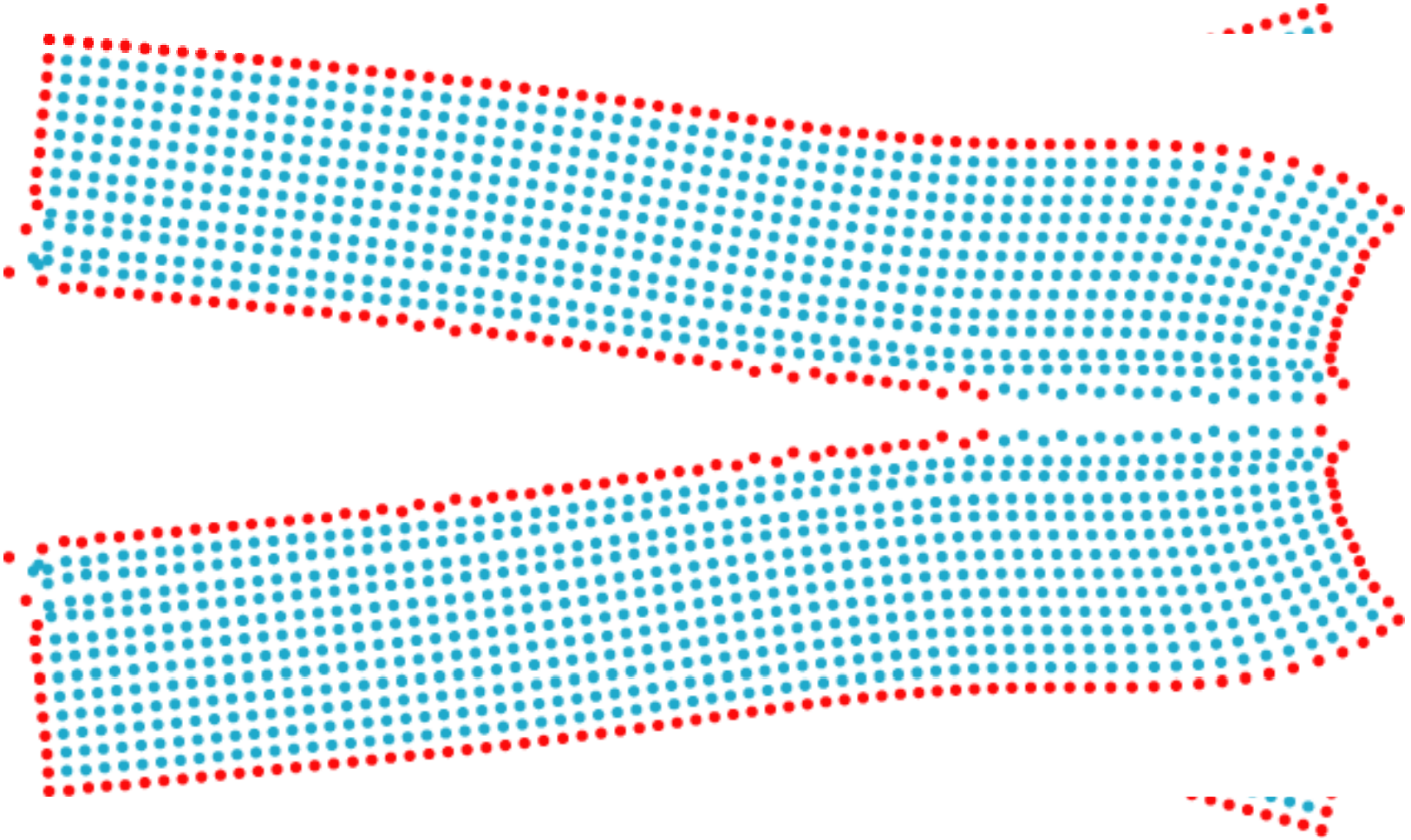


无网格法的应用



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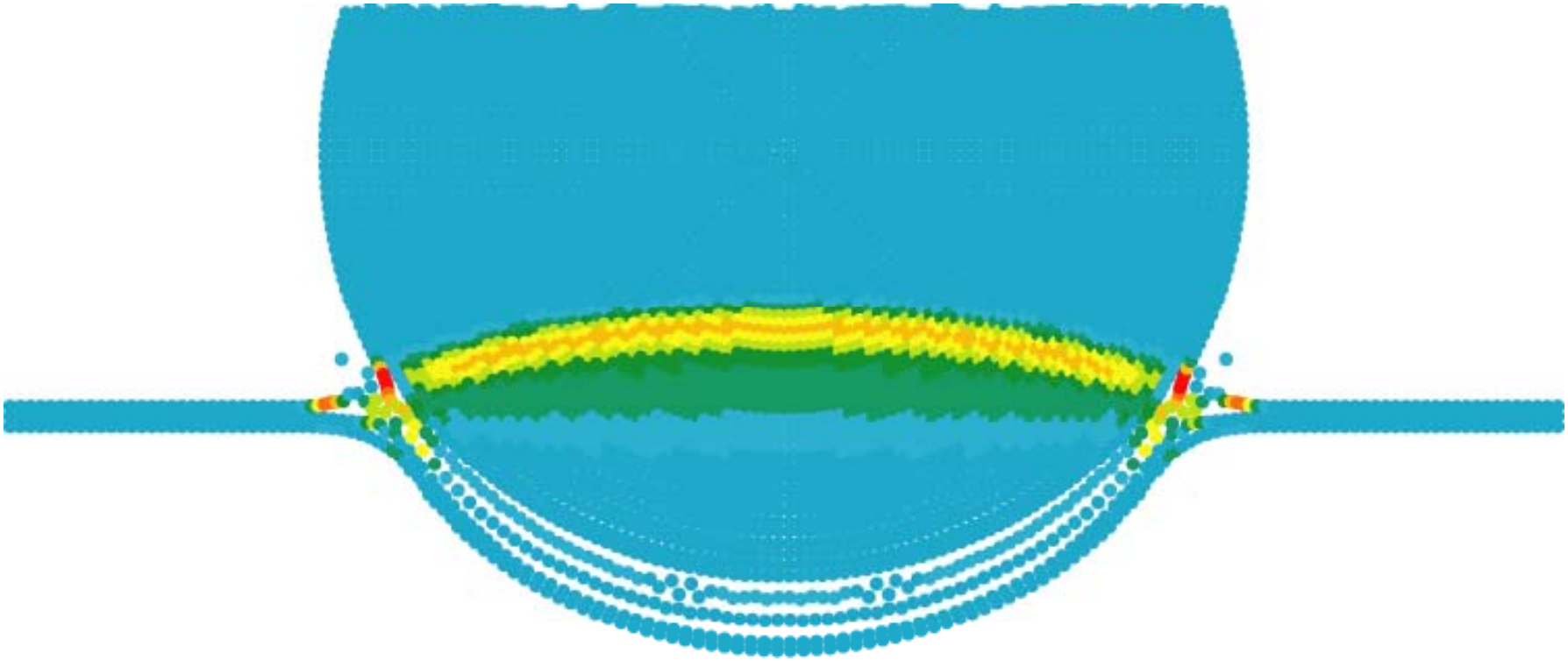

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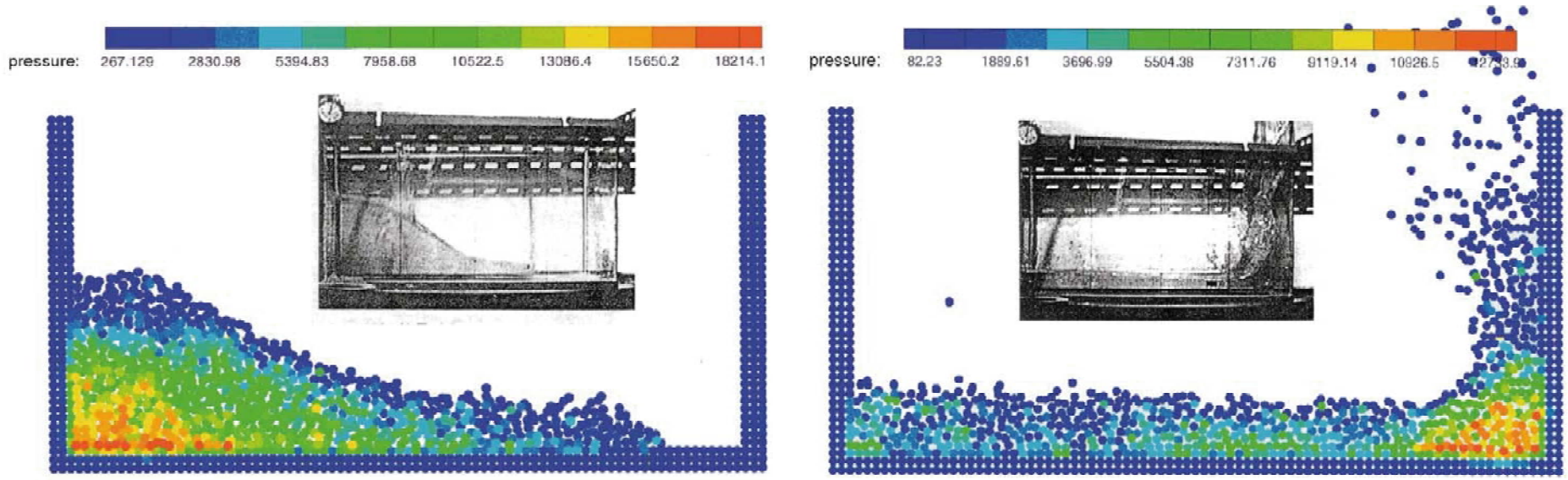
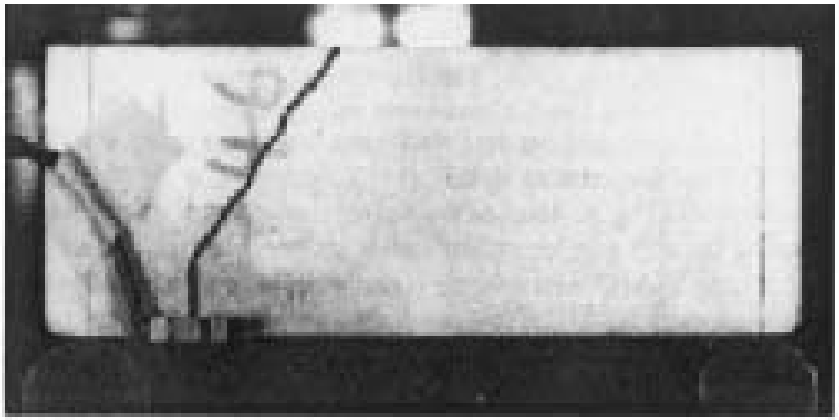
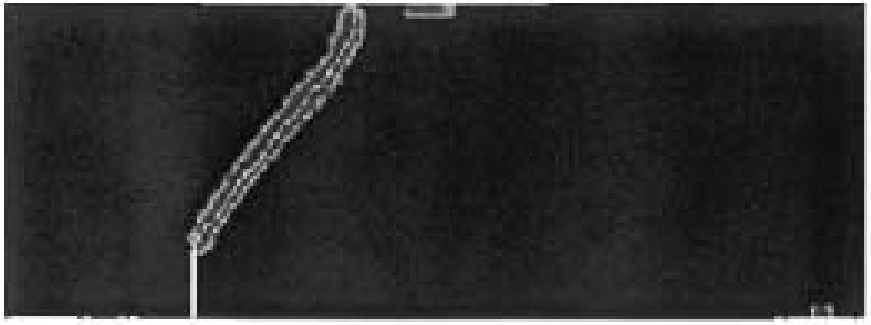

pressure: 267.129 2830.98 5394.83 7958.68 10522.5 13086.4 15650.2 18214.1
pressure: 82.23 1889.61 3696.99 5504.38 7311.76 9119.14 10926.5

无网格法的应用



无网格法的应用





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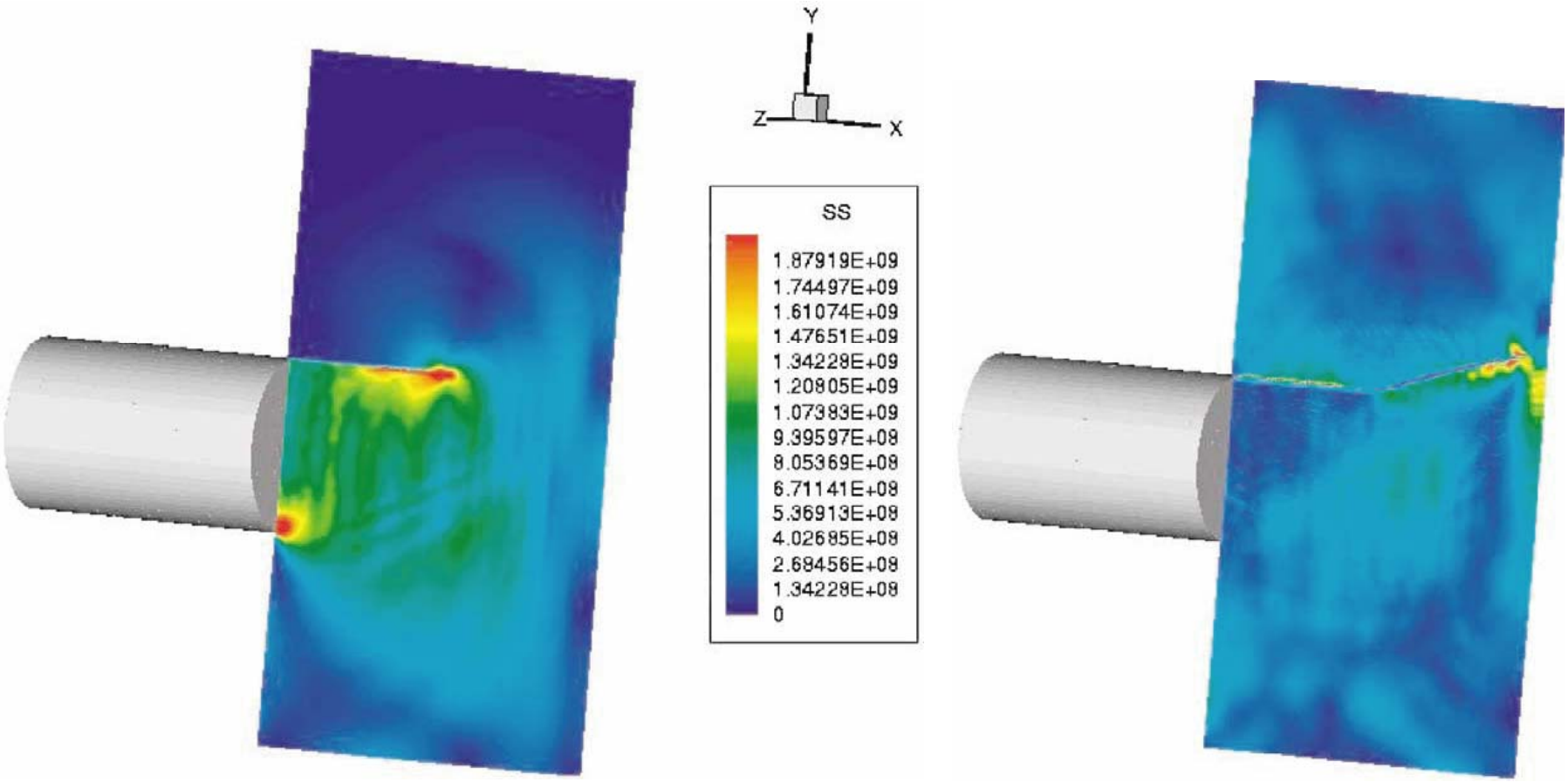
Y
Z
X
SS
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1.74497E+09
1.61074E+09
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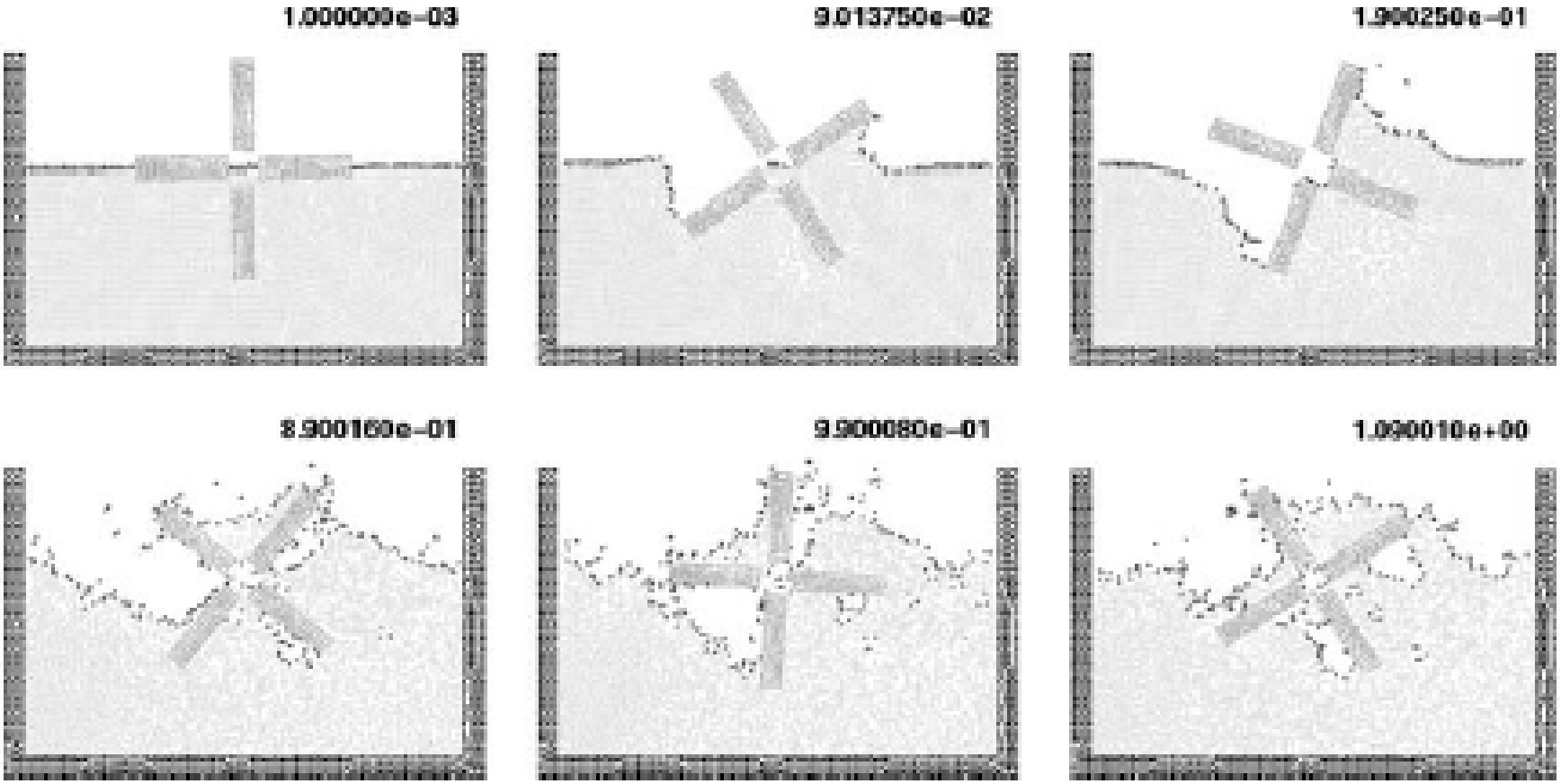
1.34228E+09
1.20805E+09
1.07383E+09
9.39597E+08
8.05369E+08
6.71141E+08
5.36913E+08
4.02685E+08
2.68456E+08
1.34228E+08
0

无网格法的应用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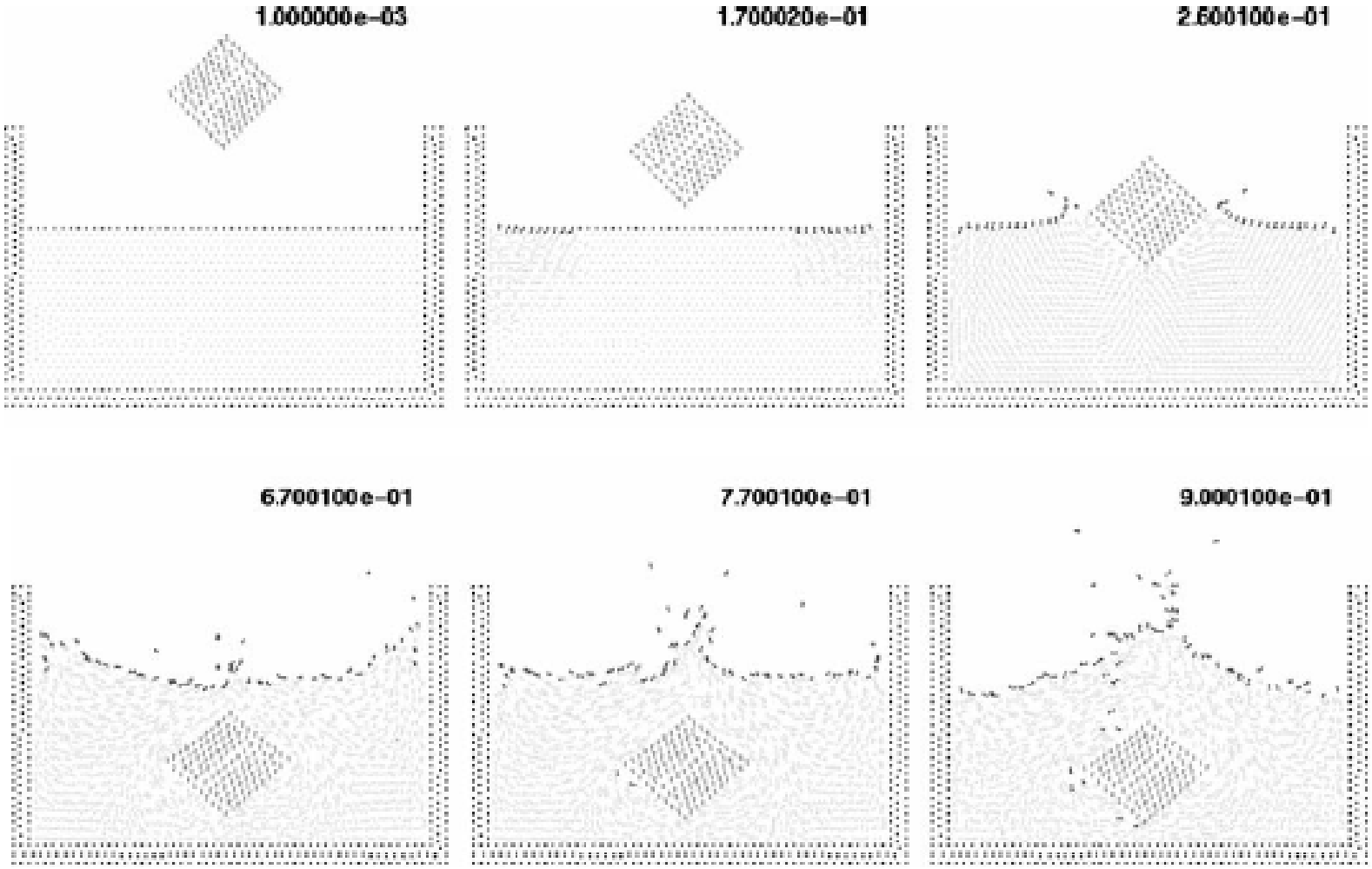
无网格法的应用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9.000100e-01

无网格法的应用

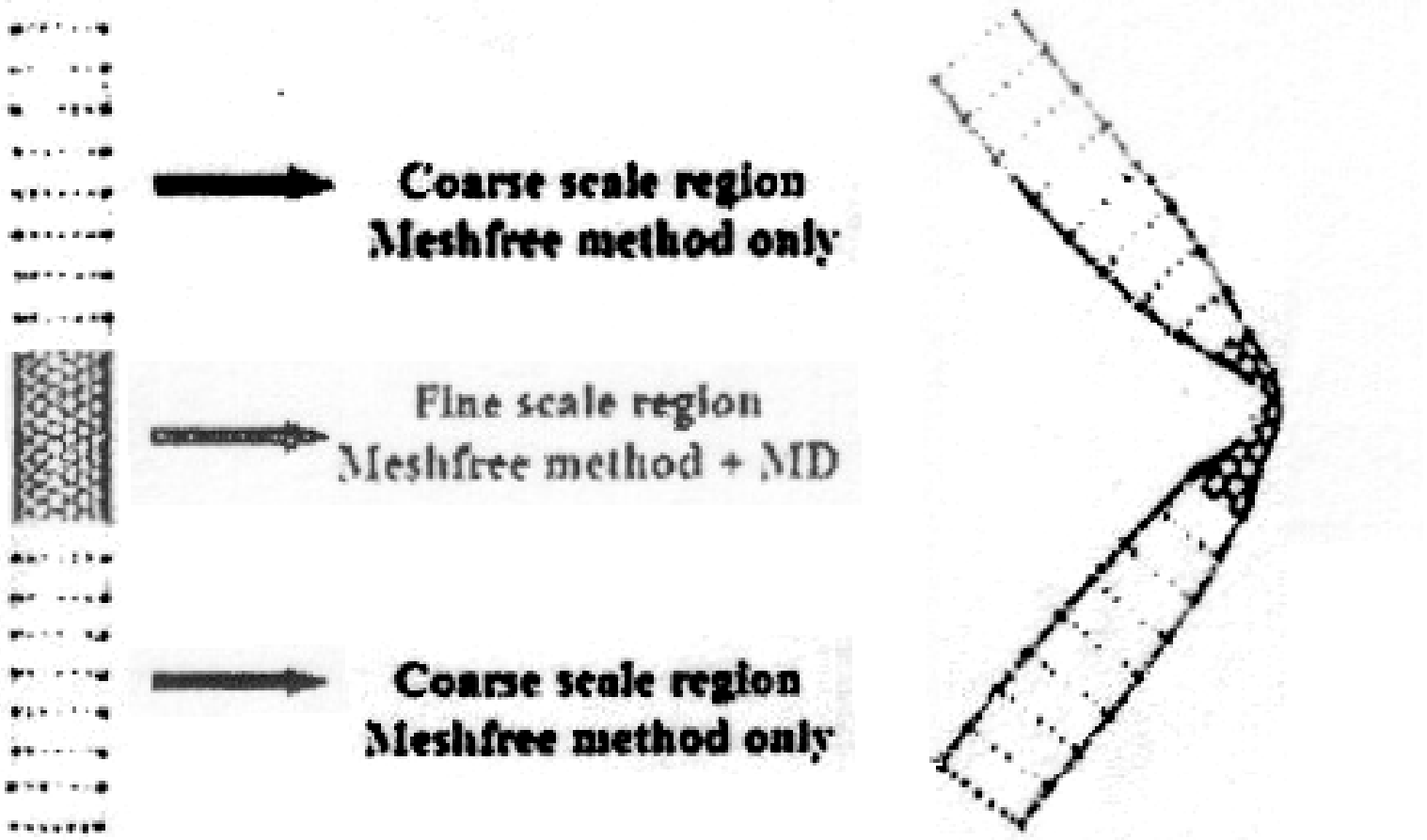
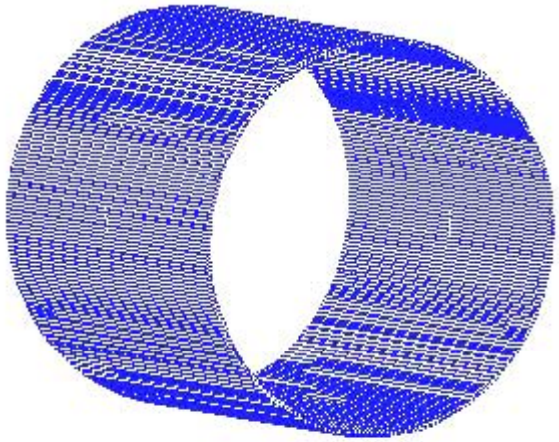


Fig. 28 Multiscale analysis of carbon nanotube

无网格法的应用

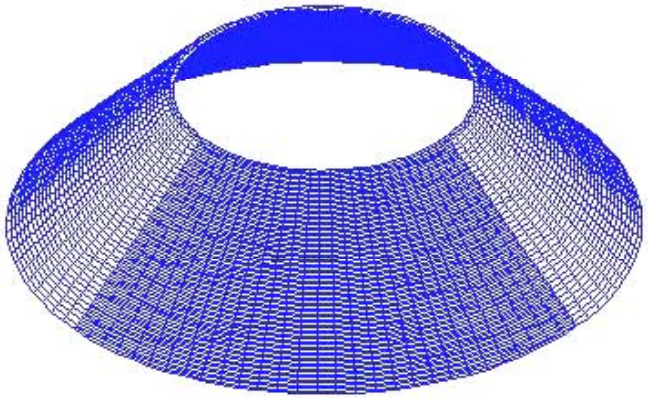
RKPM





无网格法的应用

RKPM



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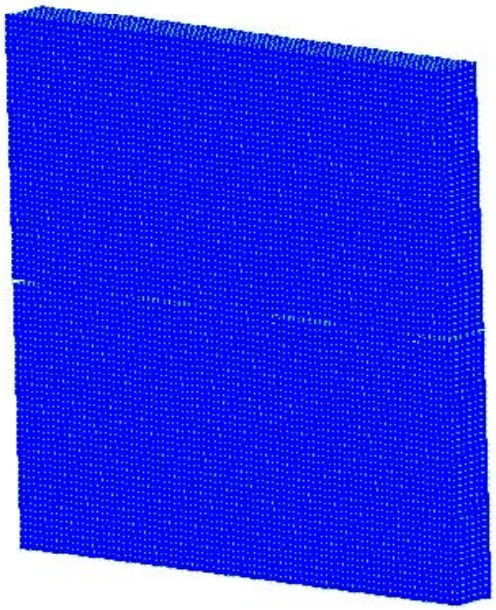
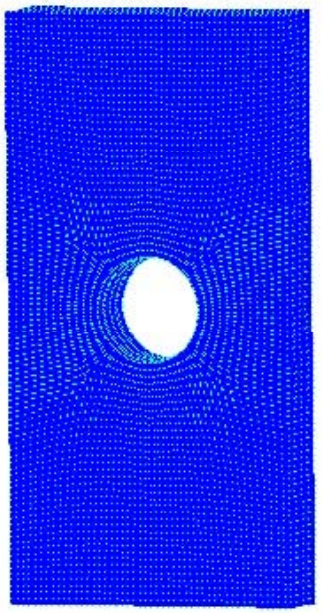


RKPM



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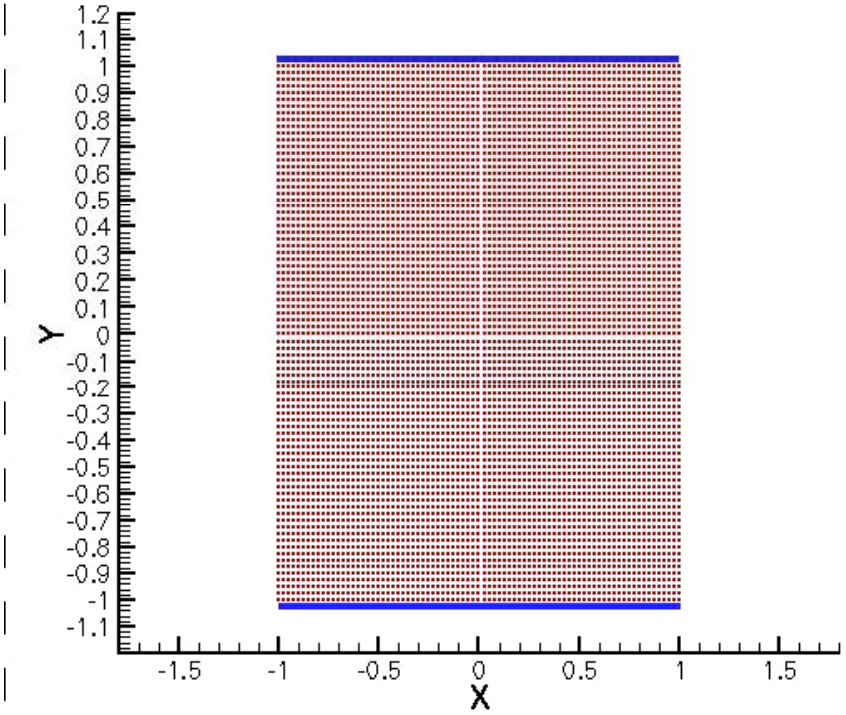
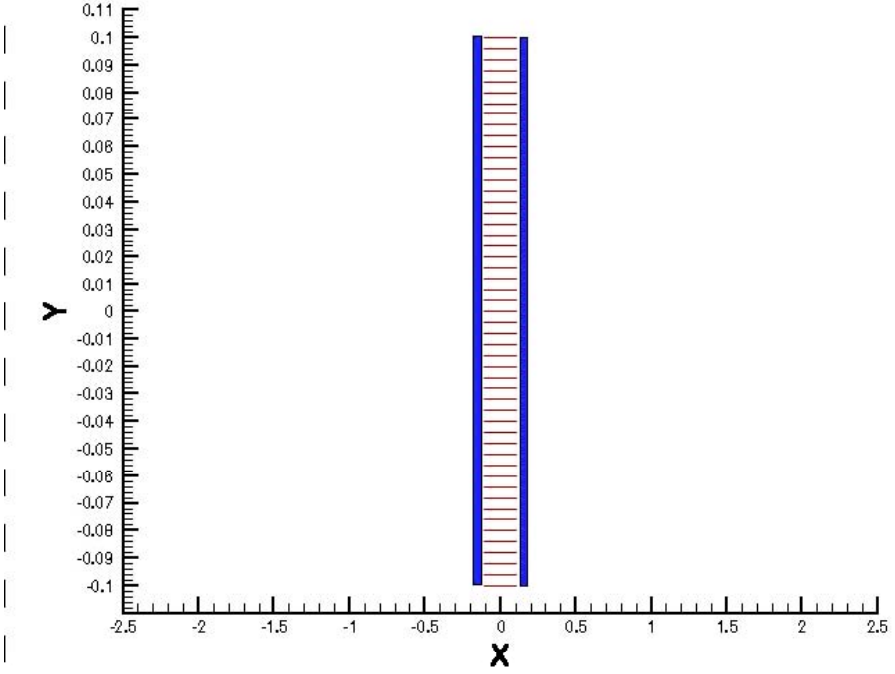
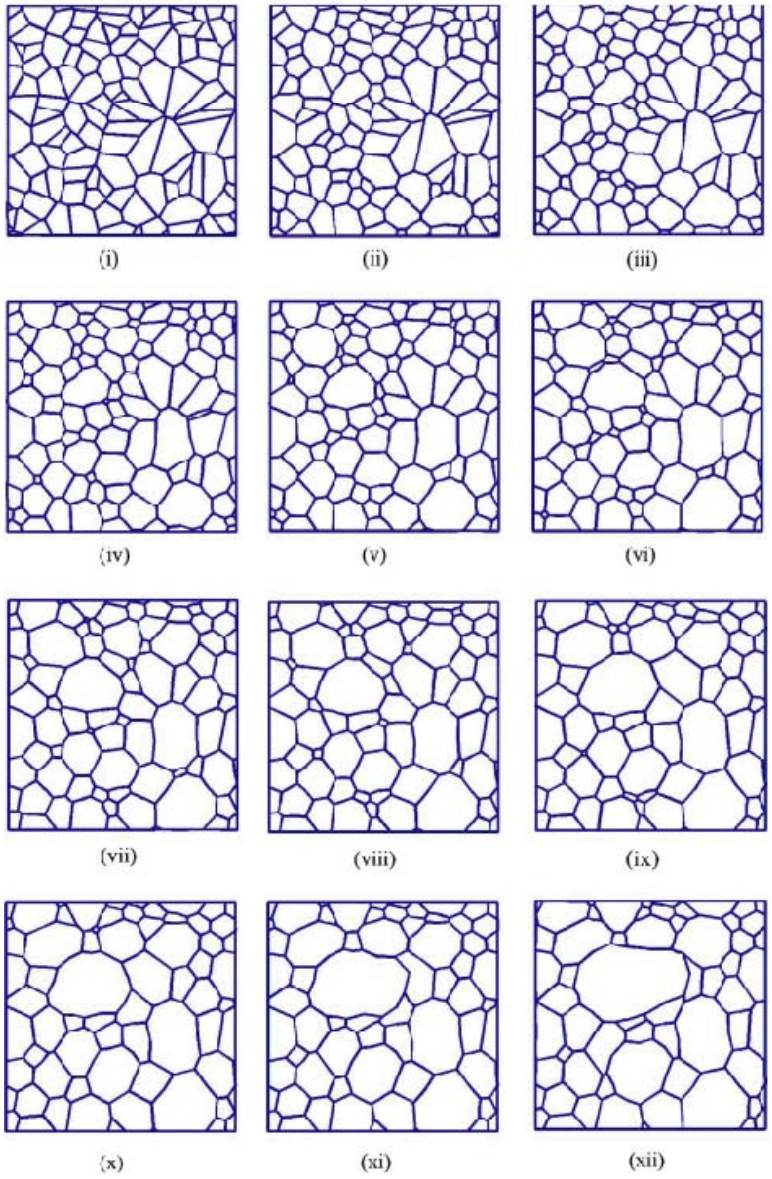


RKPM



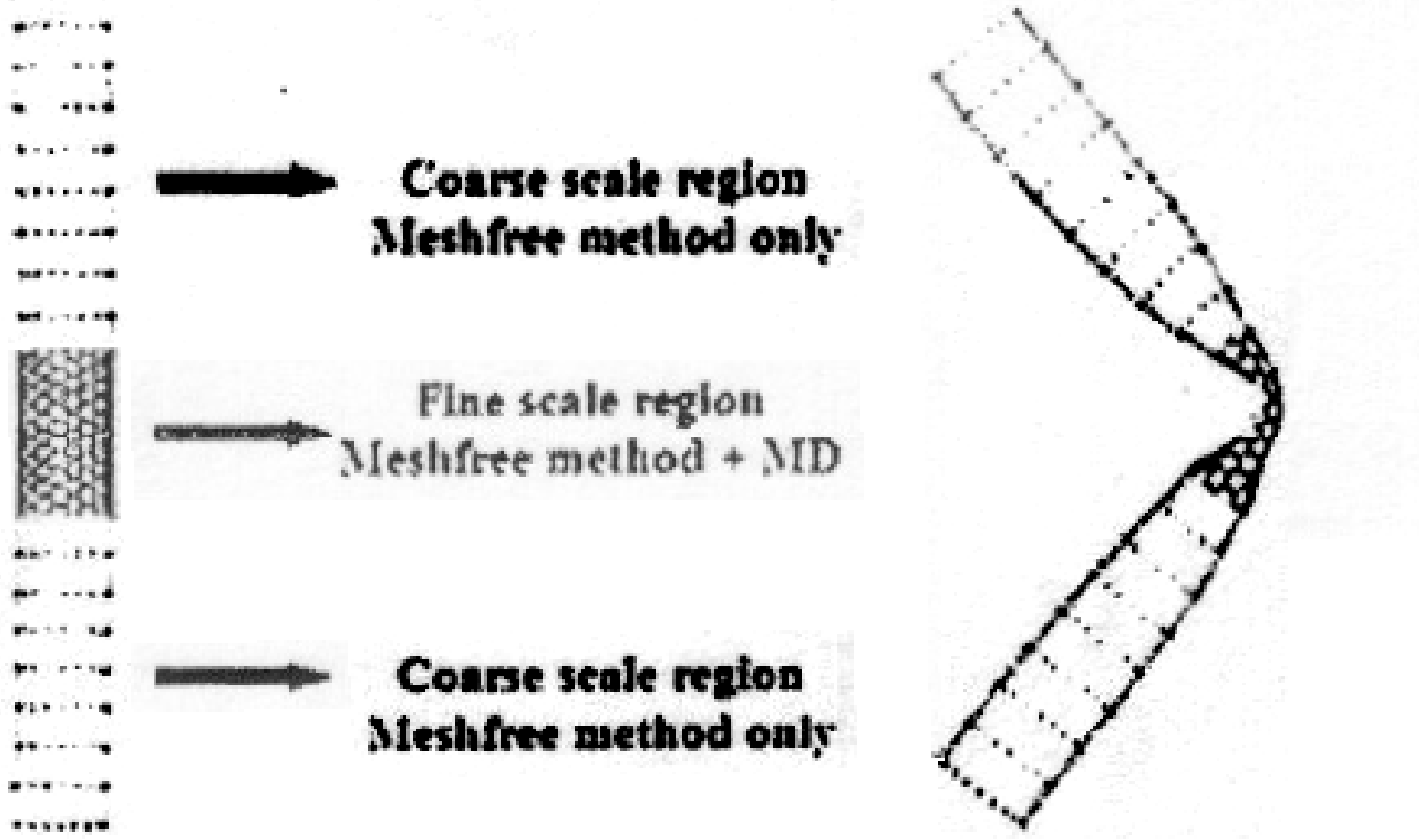
无网格法的应用



RKPM/FEM联合求解多晶材料中晶粒的生长过程

JS Chen

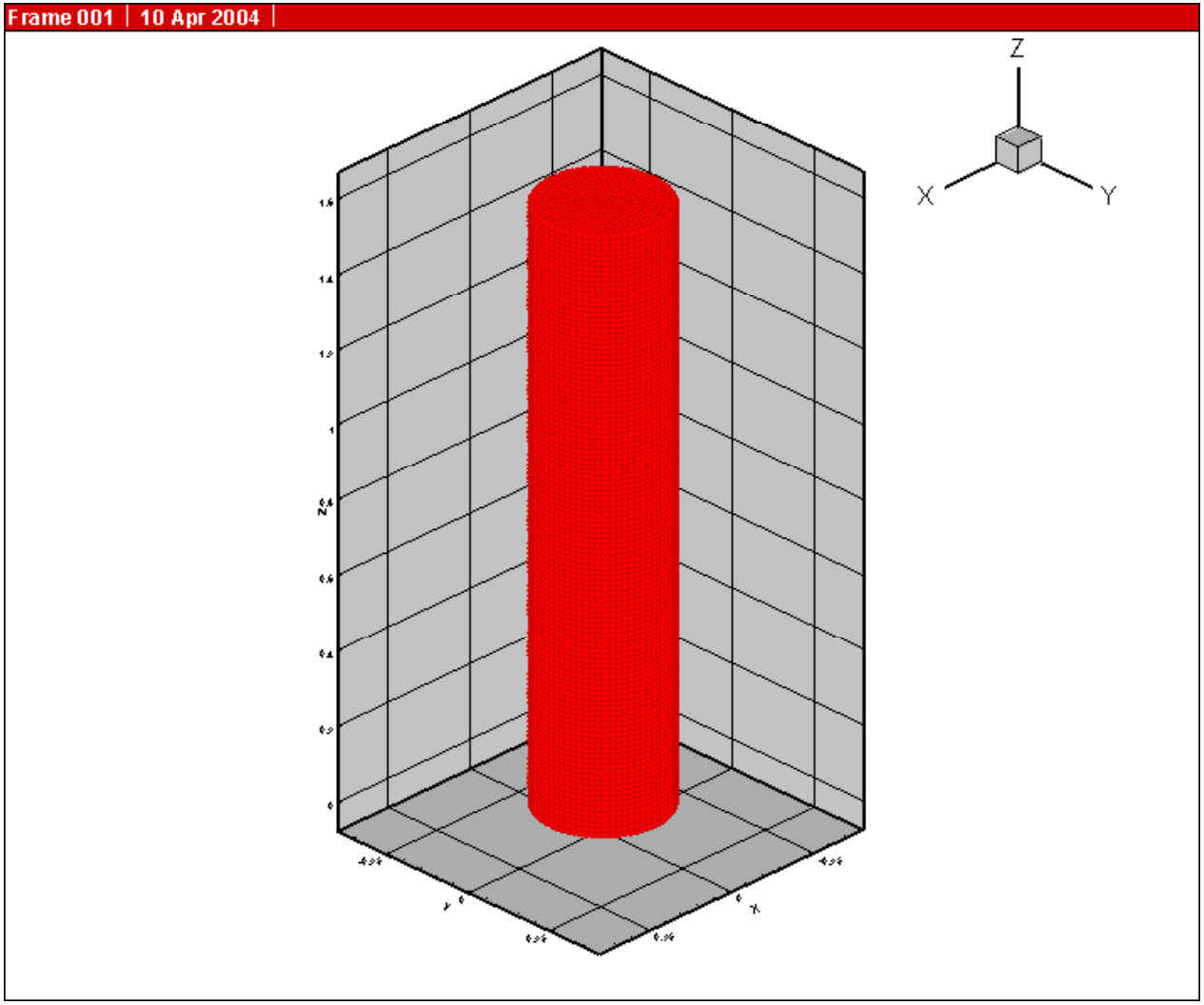
无网格法的应用



RKPM
+ MD

Fig. 28 Multiscale analysis of carbon nanotube

无网格法的应用



Taylor杆

王裴等

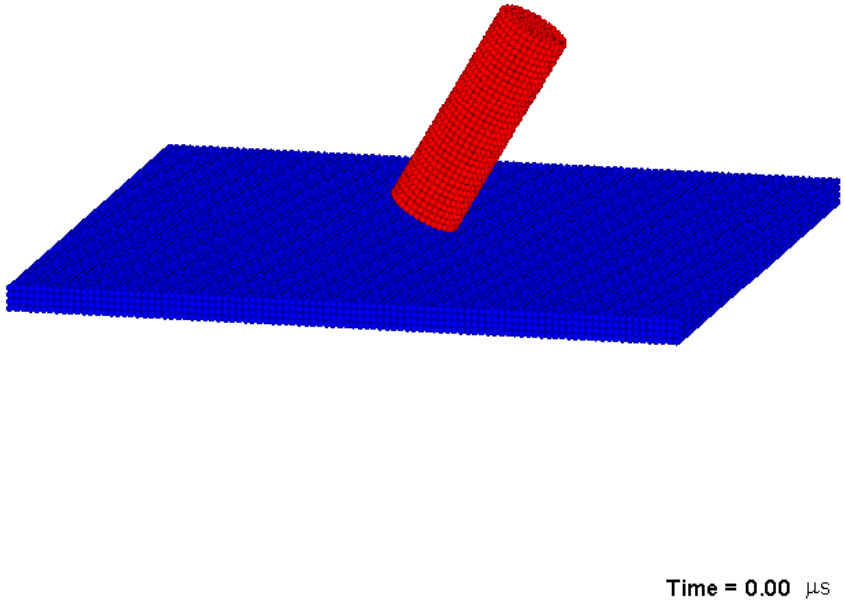
撞击速度227m/s
SG本构模型
总粒子数50310

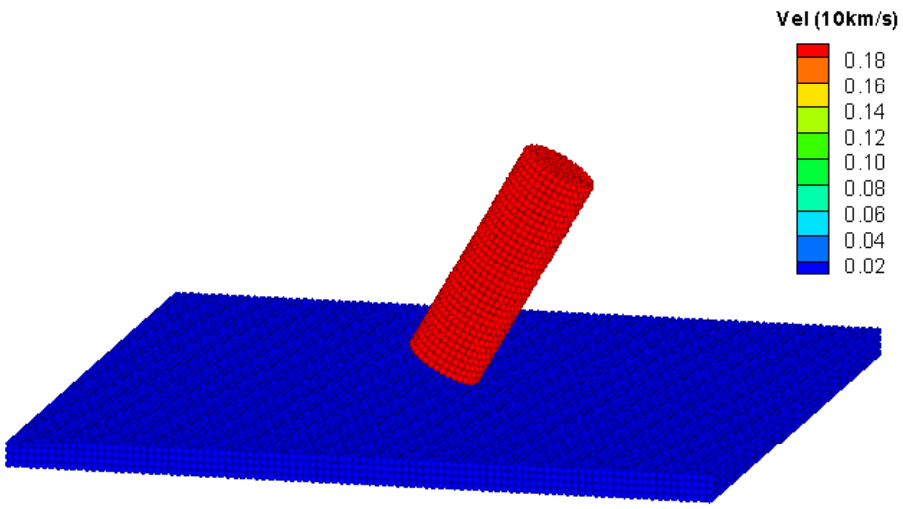
Numerical fracture

无网格法的应用

圆柱体弹斜侵彻

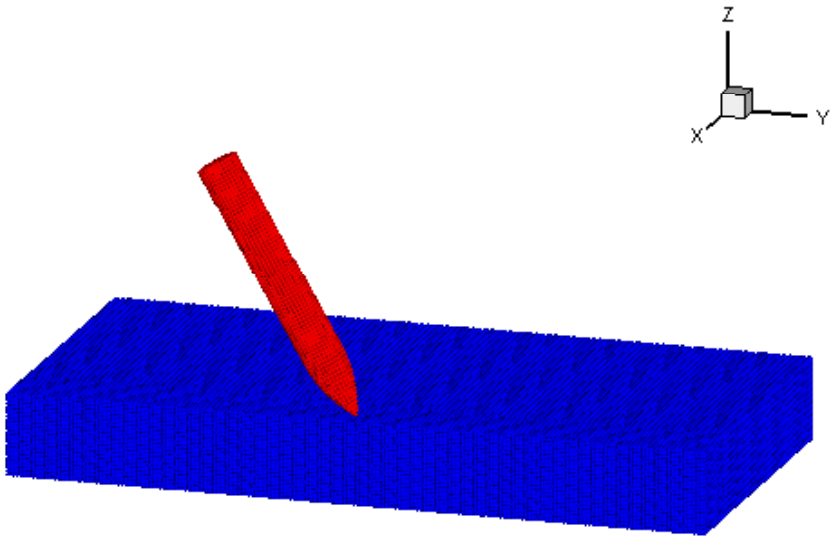
王裴等
总粒子数43498
弹：钢，直径1.1cm，高度6.6cm
攻角30°，速度2km/s
靶：铝，10cm×10cm×0.8cm





无网格法的应用

尖头弹斜侵彻

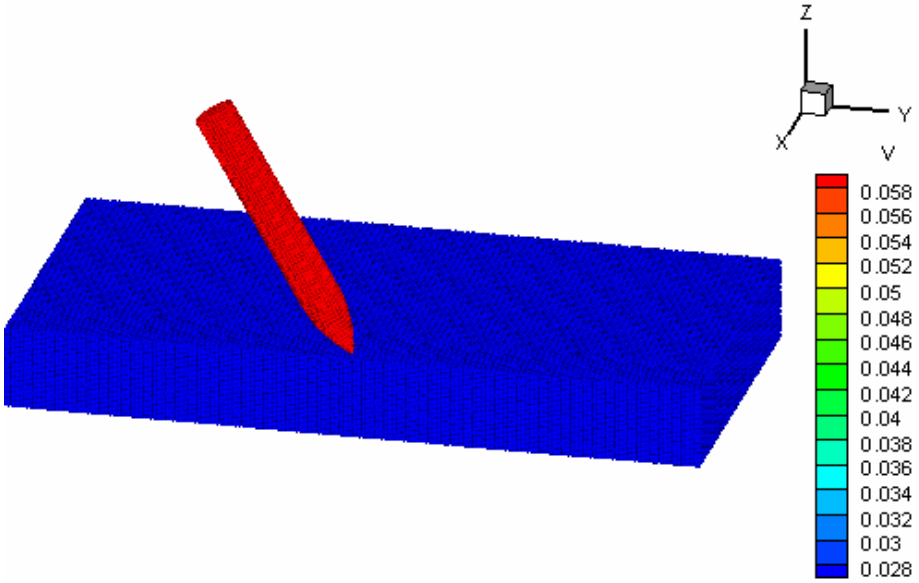


王裴等

总粒子数1,454,255

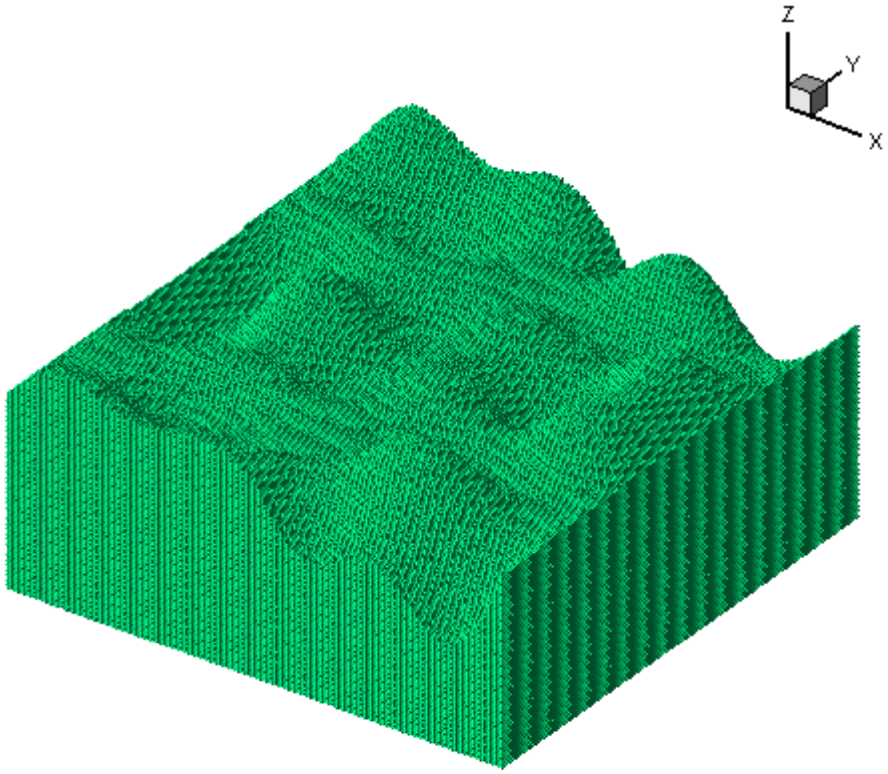
钢弹：攻角30°，初始速度600m/s，
剩余速度440m/s，实验值460m/s

铝靶：23.6cm×23.6cm×2.6cm



无网格法的应用

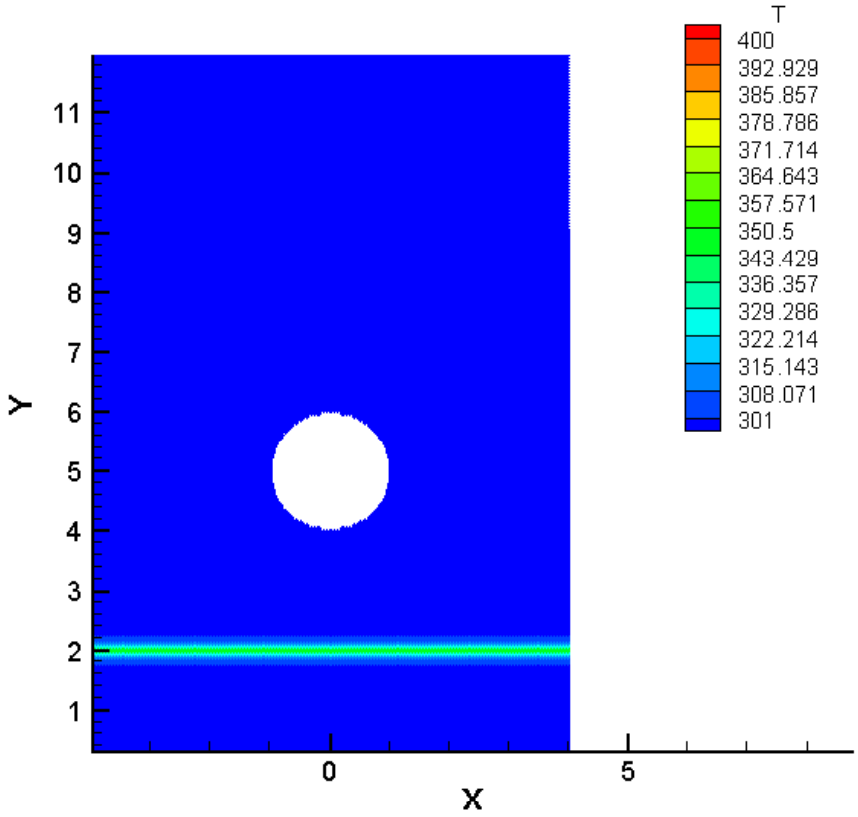
三维微射流



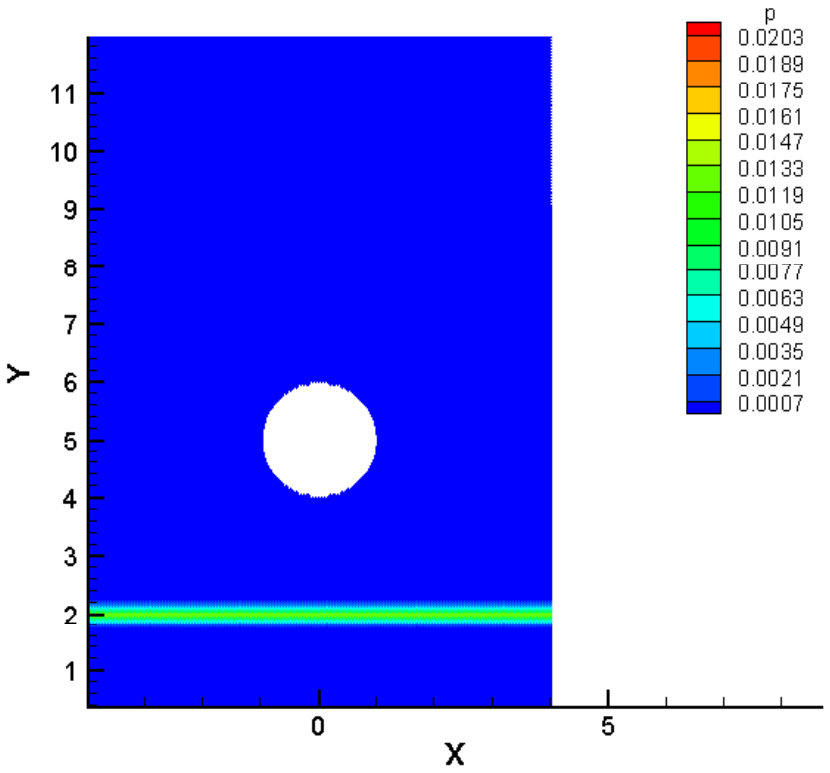
王裴等

总粒子数1,527,402

无网格法的应用

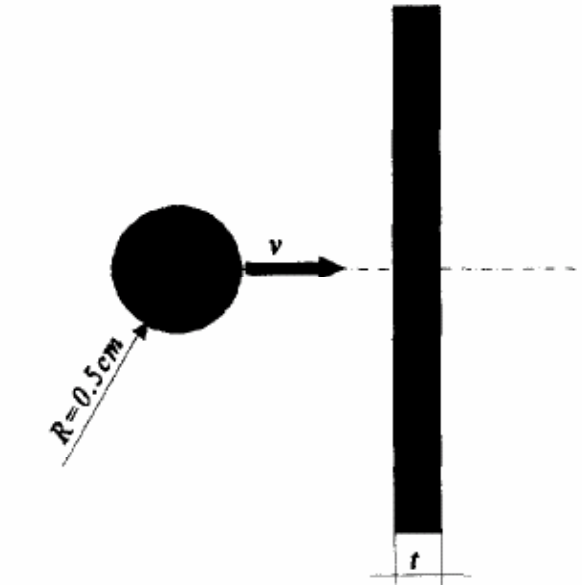


炸药“热点”问题



无网格法的应用

铝球对不同材料的碰撞



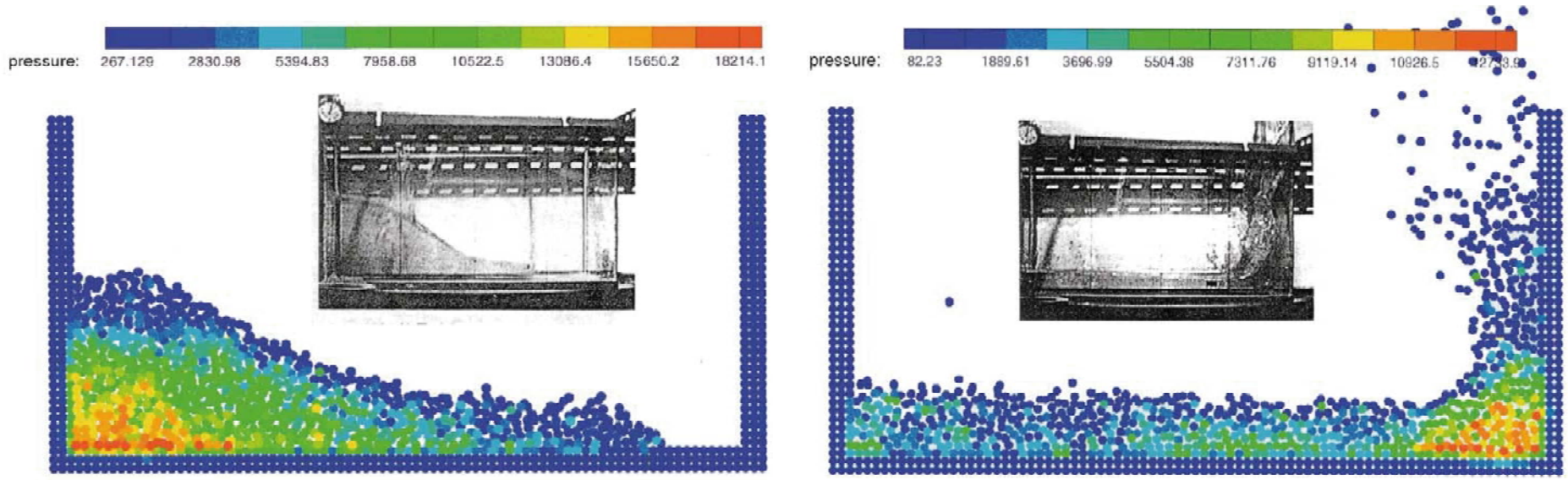
	t [cm]	v [km/s]
Al-Cu	0.15	5.75
Al-Al	0.4	6.18
Al-Pb	0.15	6.85

S. HIERMAIER等

SPH

$D_c(L/W)$	实验	模拟
Al-Cu	2.12(1.39)	2.3(1.33)
Al-Al	2.75-3.45(1.39)	3.5(1.11)
Al-Pb	2.6(1.56)	3.0(1.16)

无网格法的应用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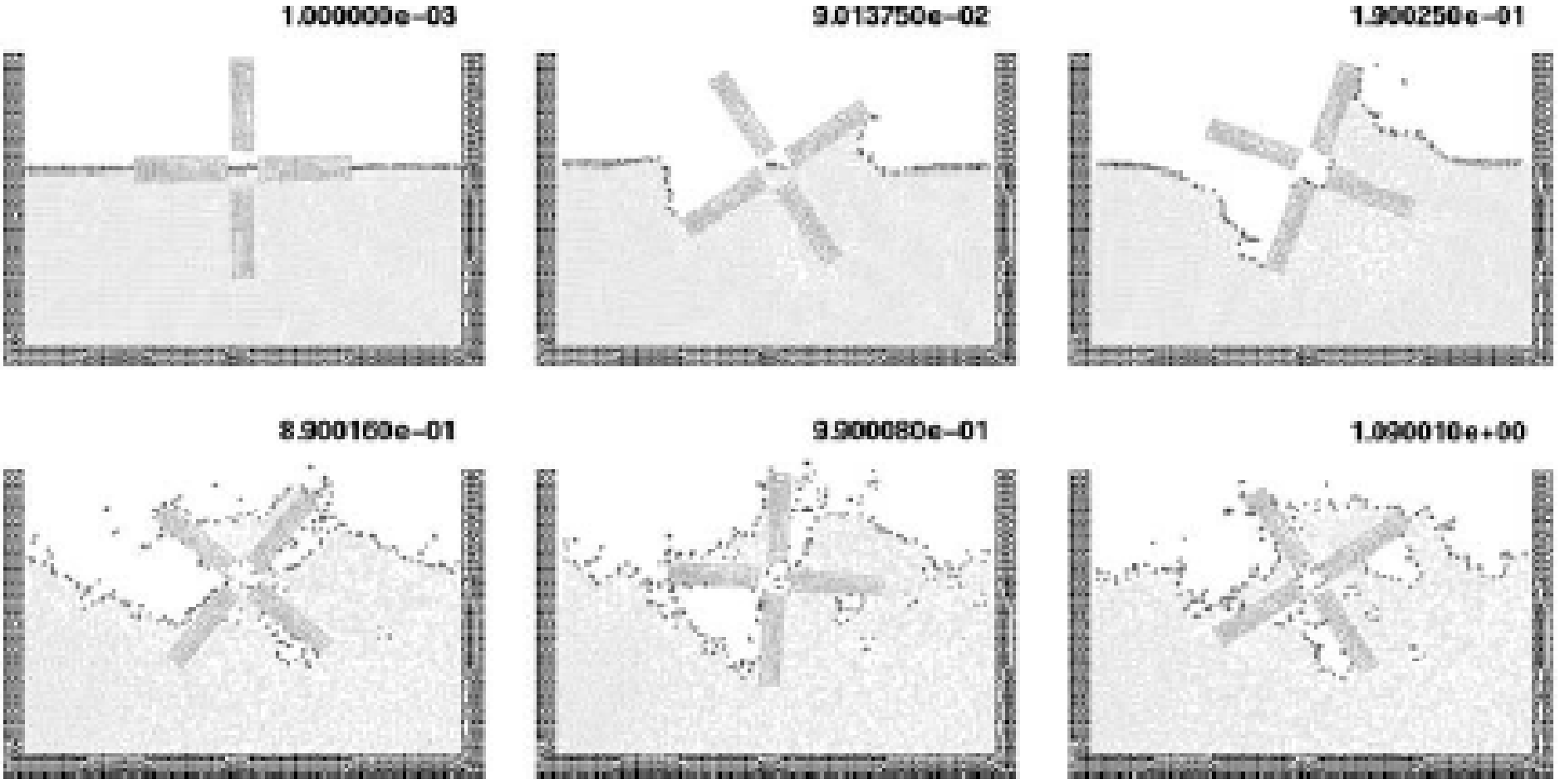
pressure: 82.23 1889.61 3696.99 5504.38 7311.76 9119.14 10926.5

无网格法的应用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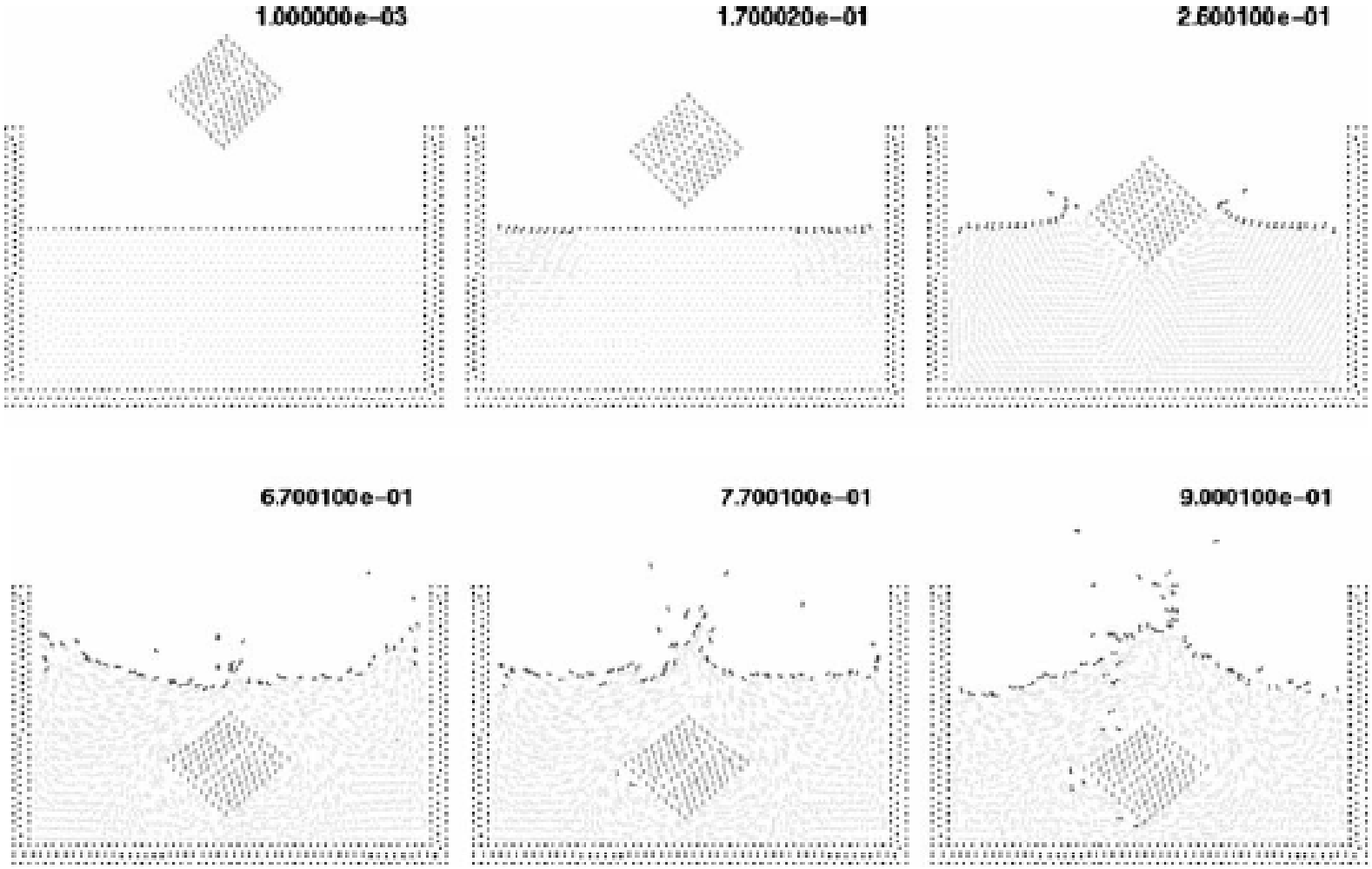
1.090010e+00

无网格法的应用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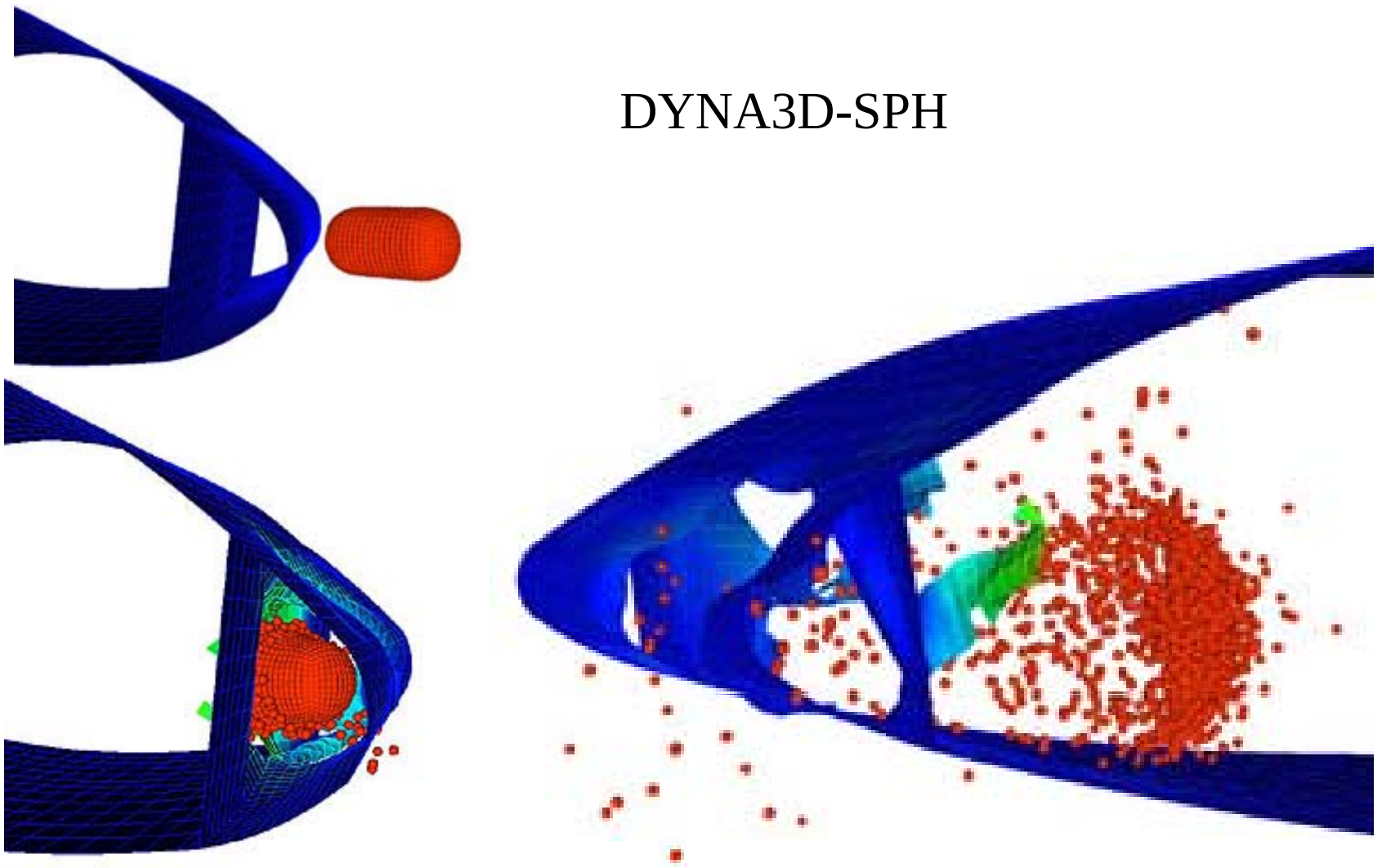

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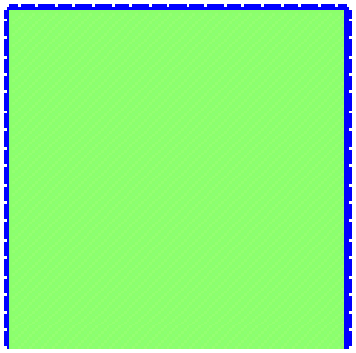
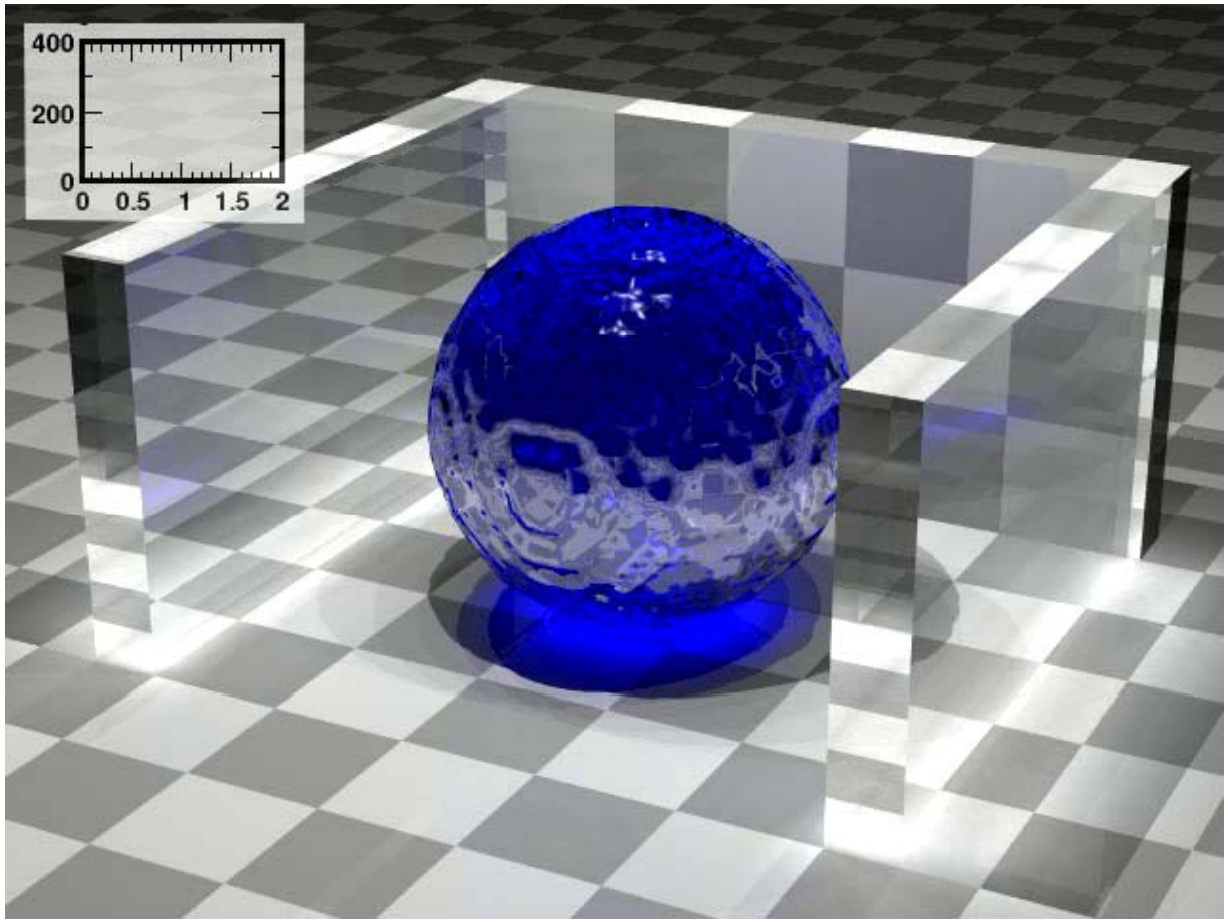
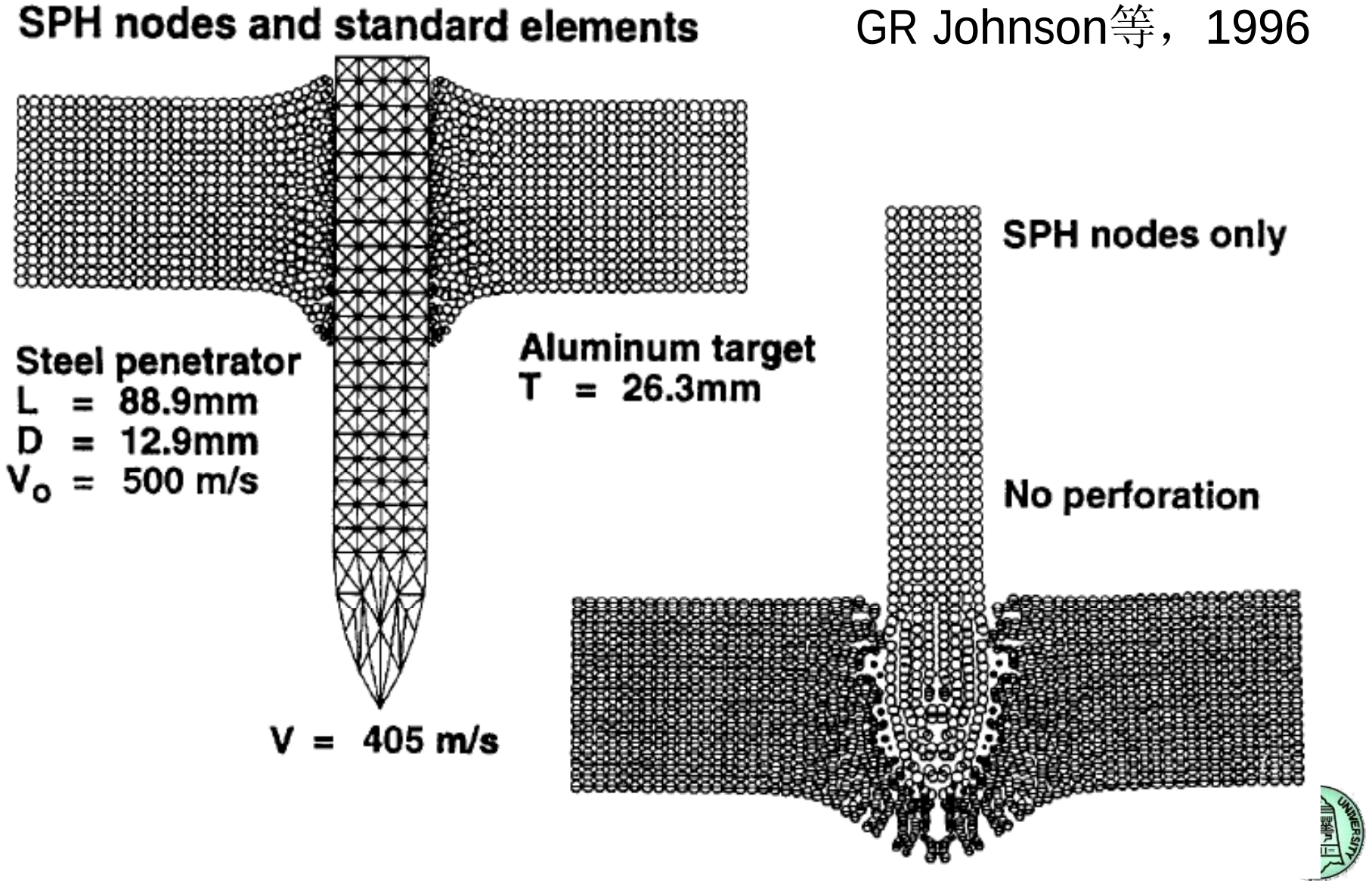


SPH模拟



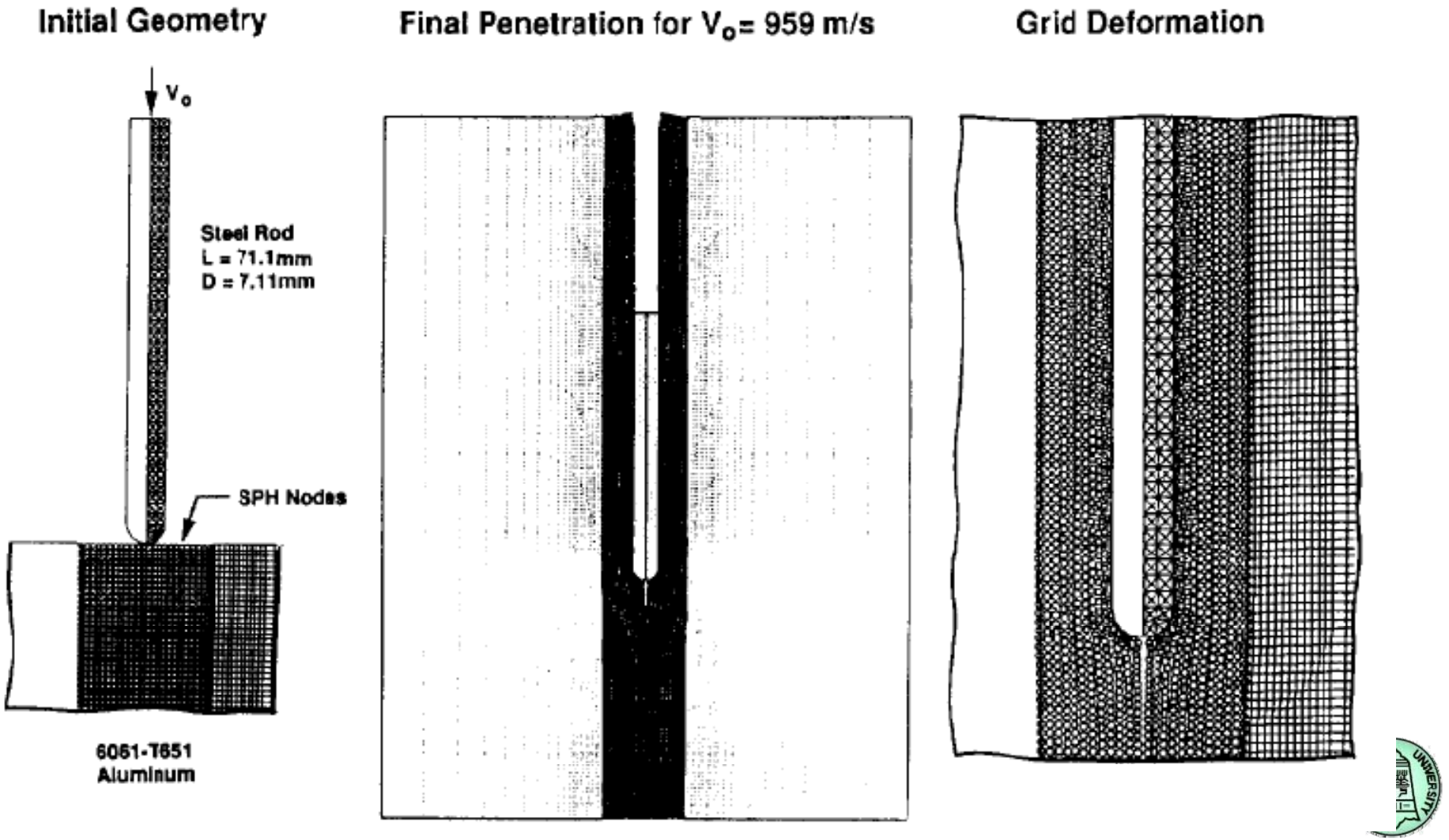
无网格法的应用


SPH nodes and standard elements
GR Johnson等，1996
Steel penetrator
L = 88.9mm
D = 12.9mm
V_o = 500 m/s
Aluminum target
T = 26.3mm
V = 405 m/s
SPH nodes only
No perforation

无网格法的应用

SPH-FEM

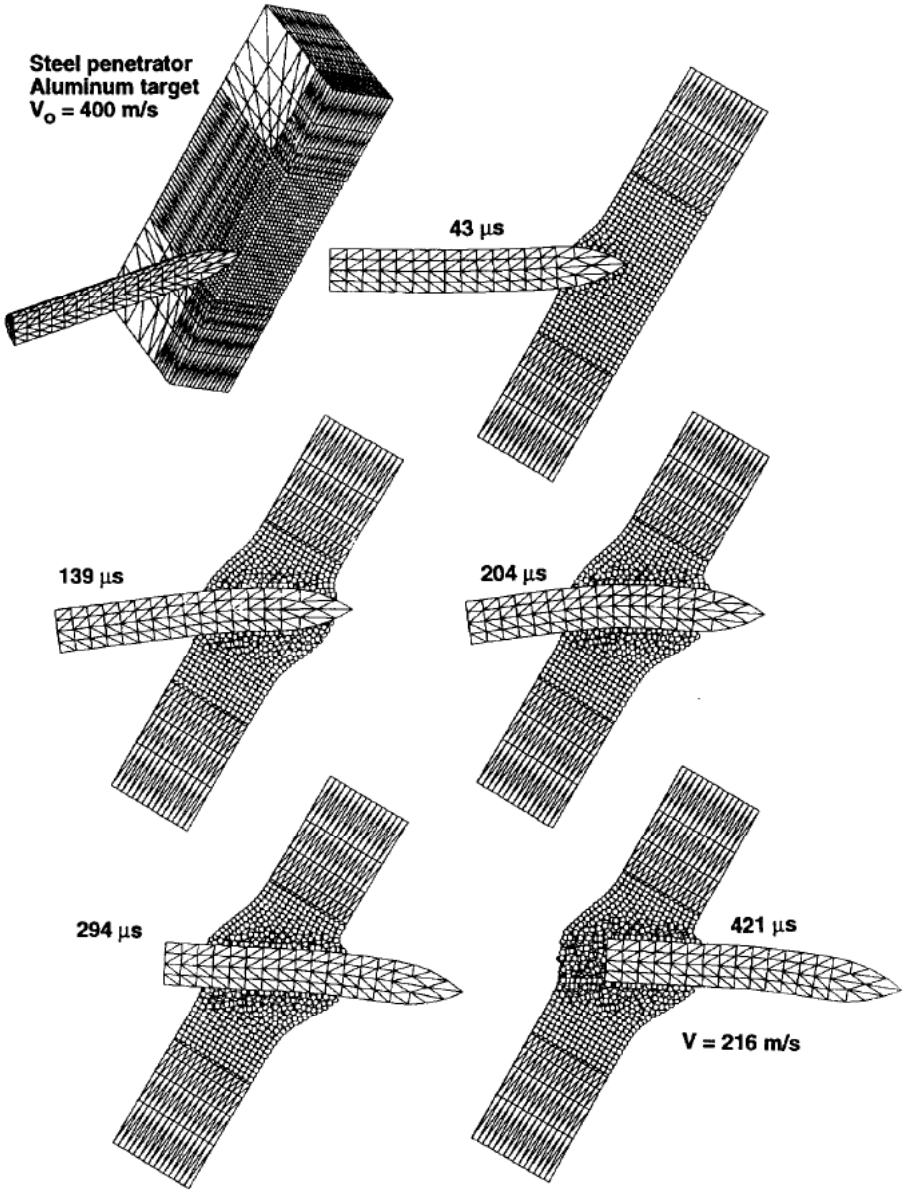
GR Johnson等，1996



无网格法的应用

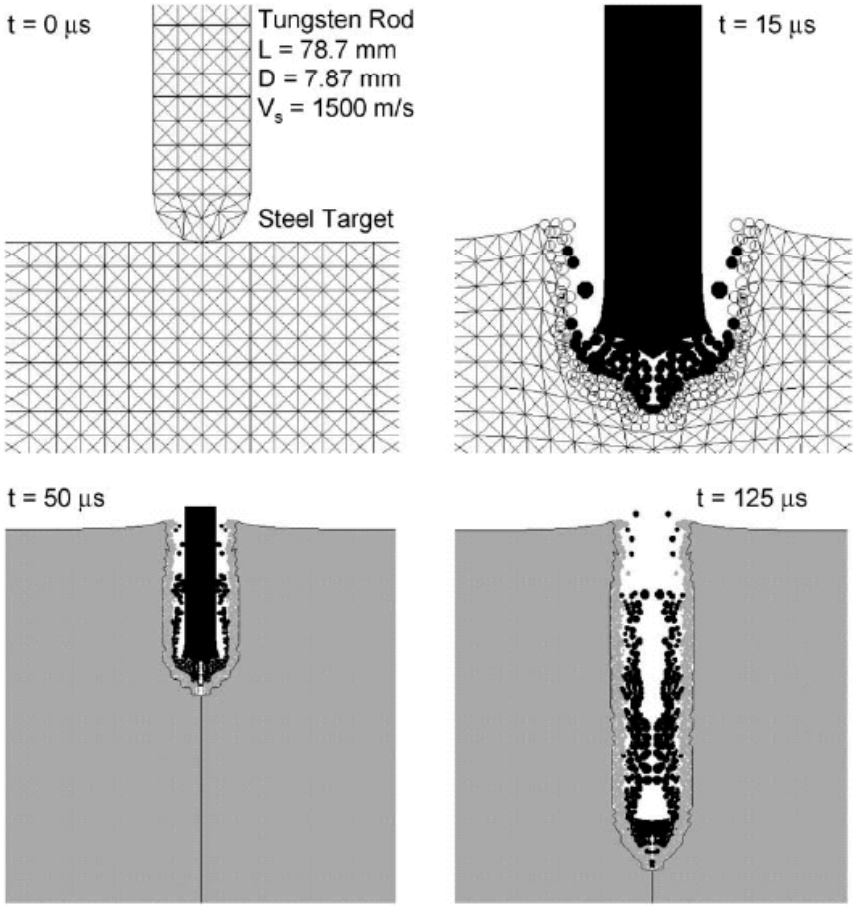
SPH-FEM

GR Johnson等，1996

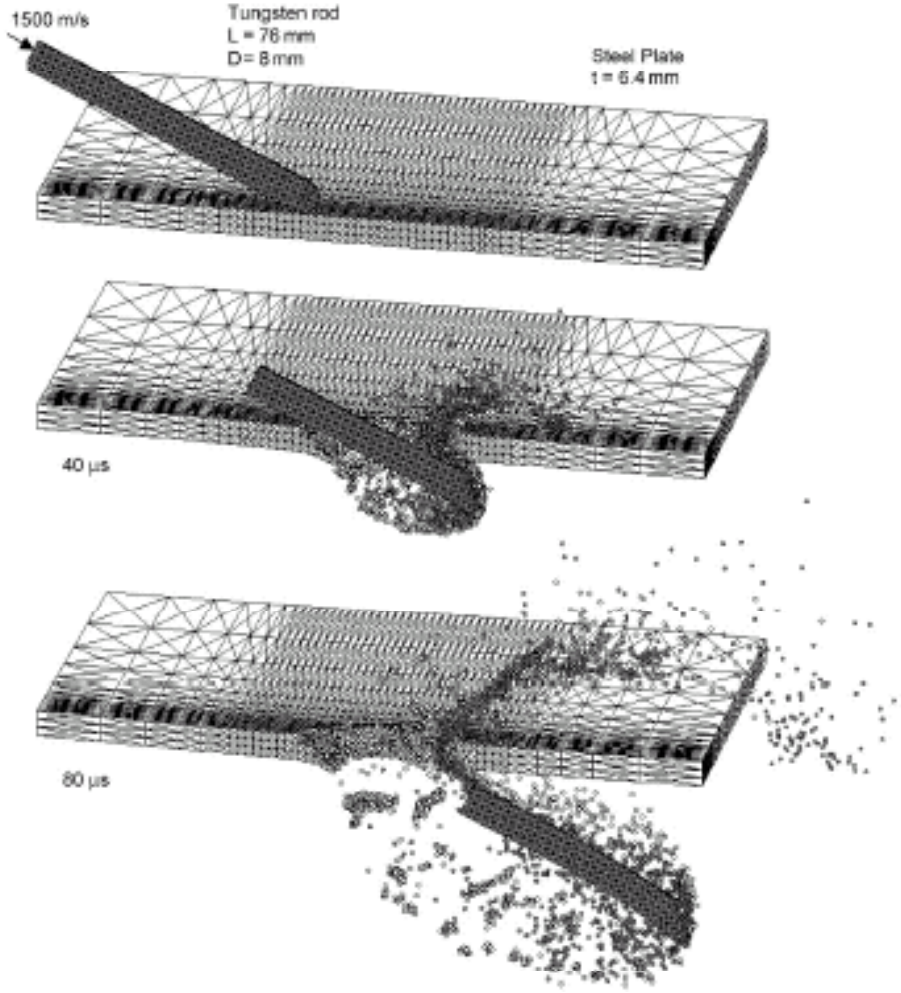


无网格法的应用

Generalized particle algorithm

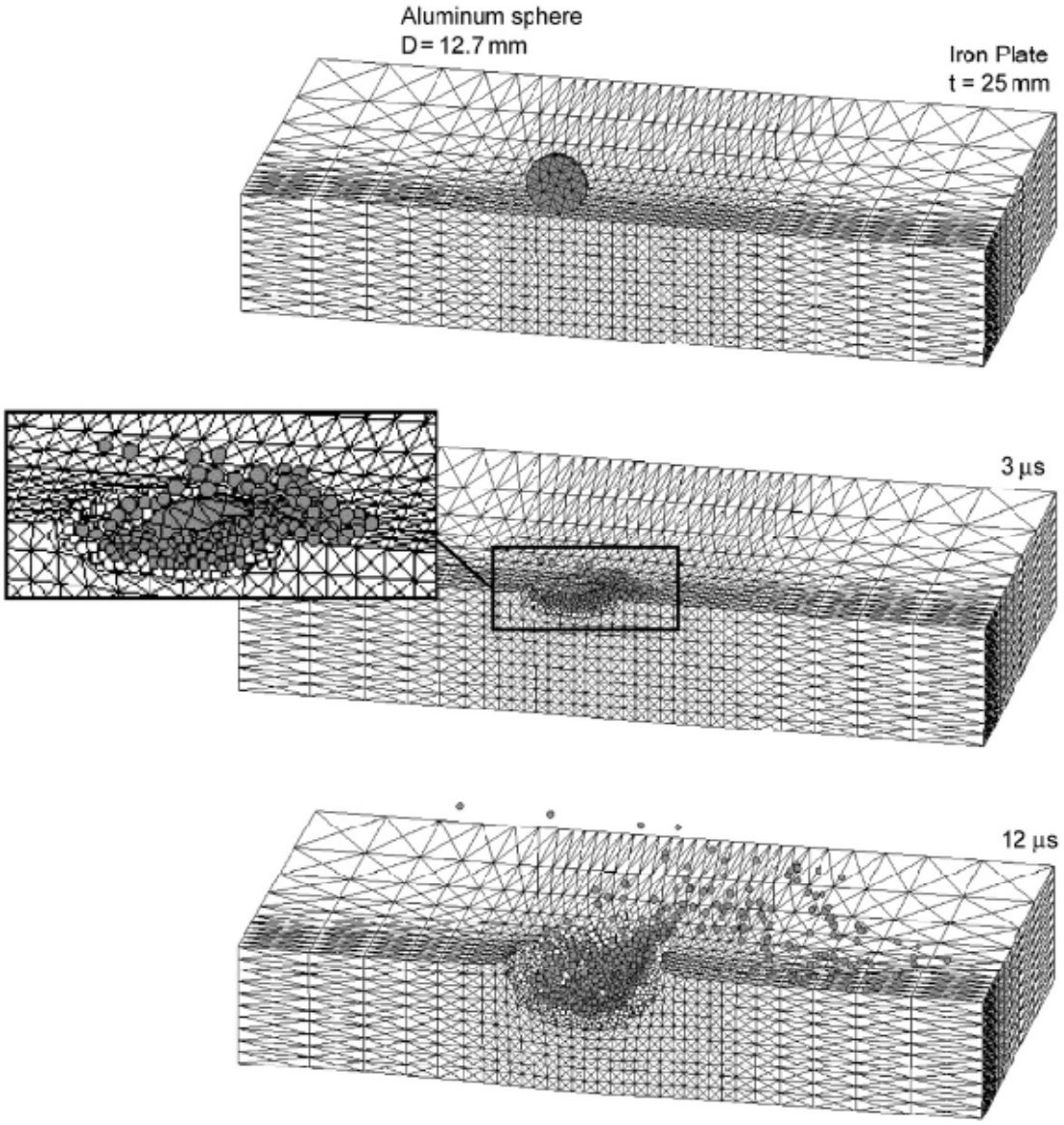


Johnson等



无网格法的应用

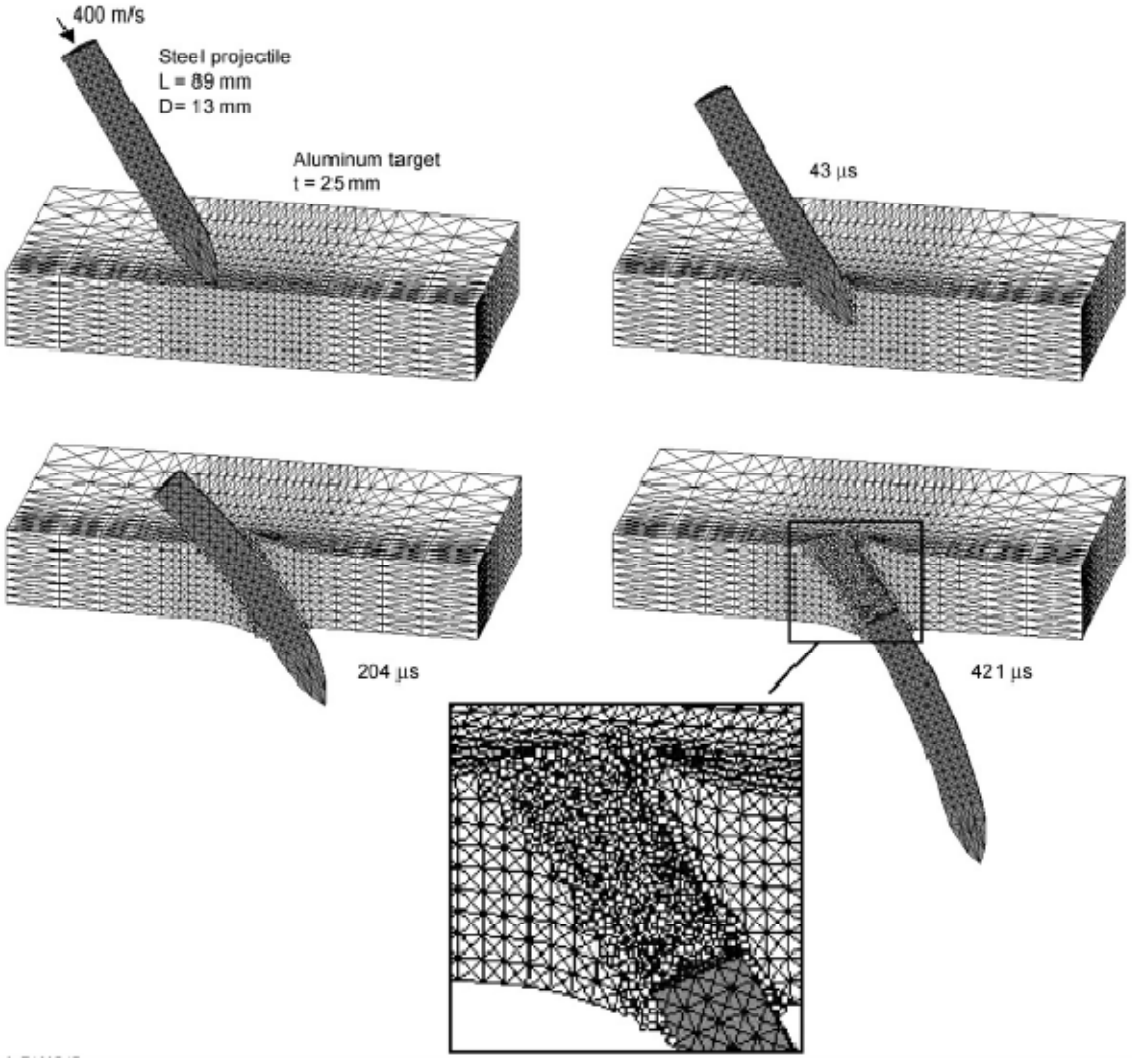
Generalized particle algorithm



Impact at 4km/s, with an obliquity of 30° from normal

无网格法的应用

Generalized particle algorithm



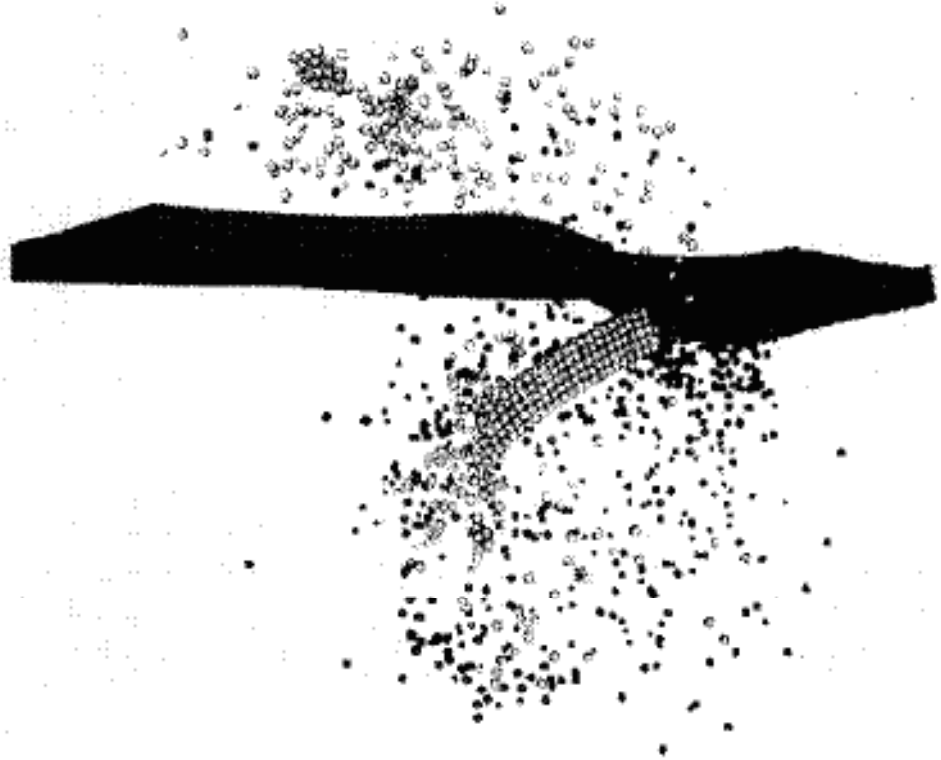
Impact at 400m/s, with an obliquity of 30° from normal

无网格法的应用

Particle-finite element method



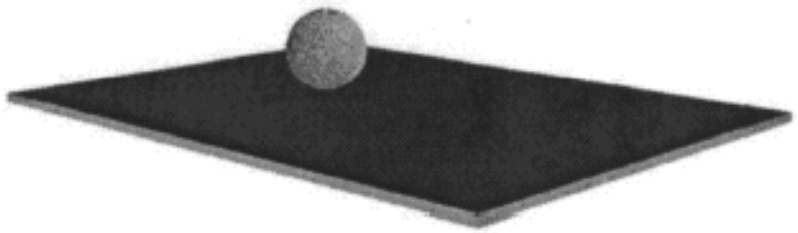
Deforming spherical particles, interacting in both the mechanical and thermal domains



E. P. Fahrenthold等,1997, 1999
University of Texas, Austin

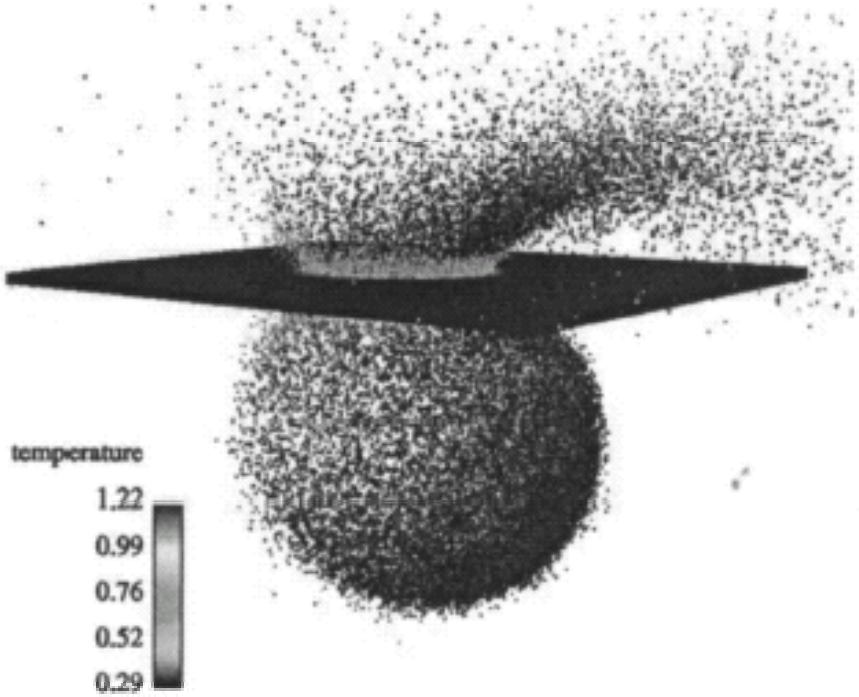
无网格法的应用

Particle-finite element method



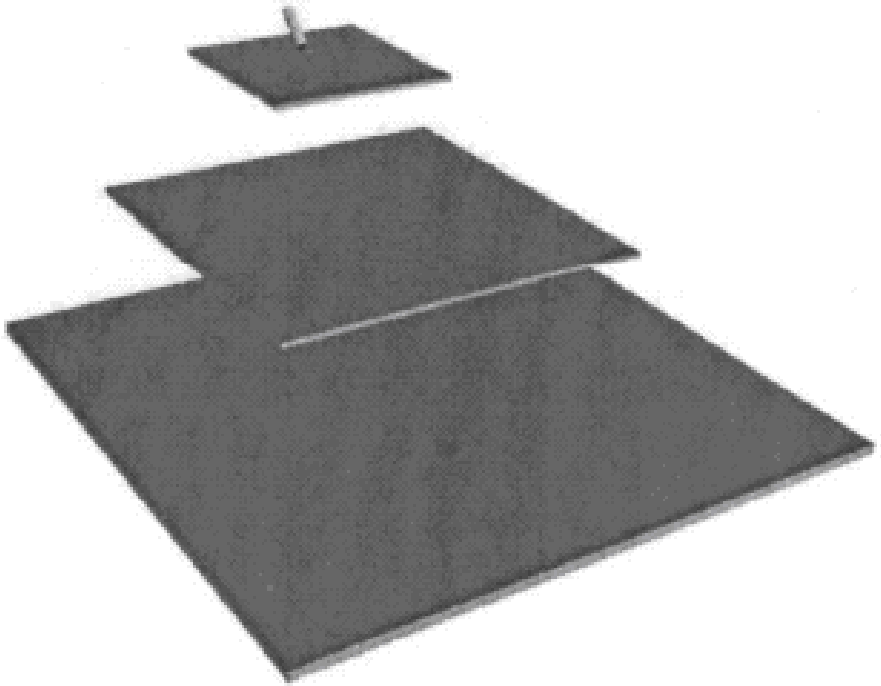
E. P. Fahrenthold等

铝球对铝板冲击



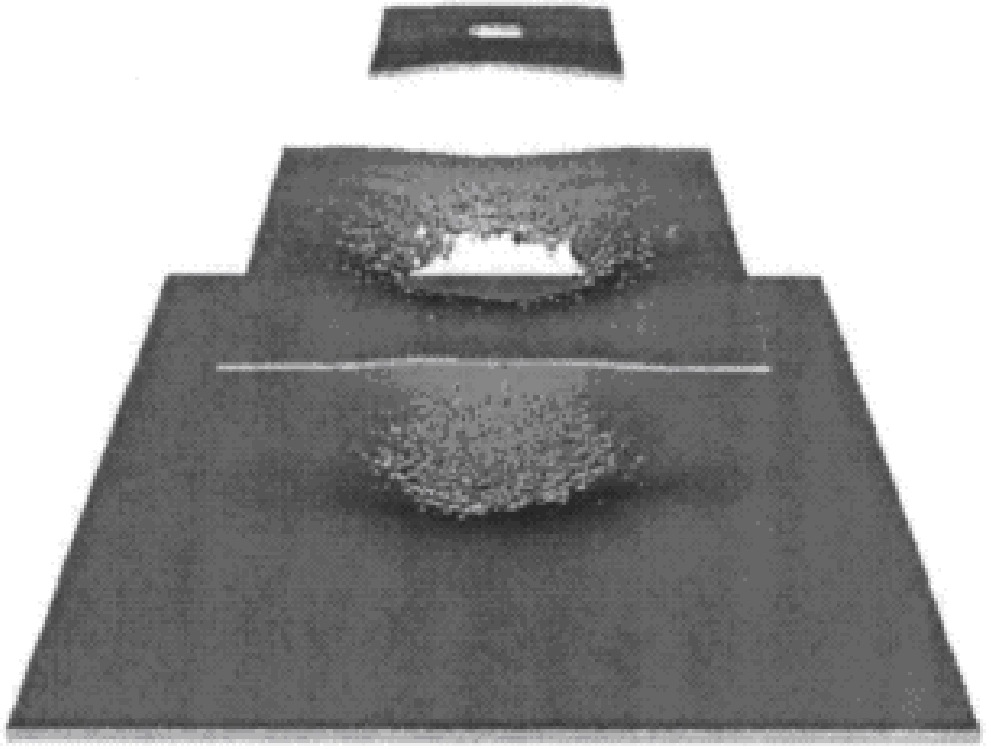
无网格法的应用

Particle-finite element method

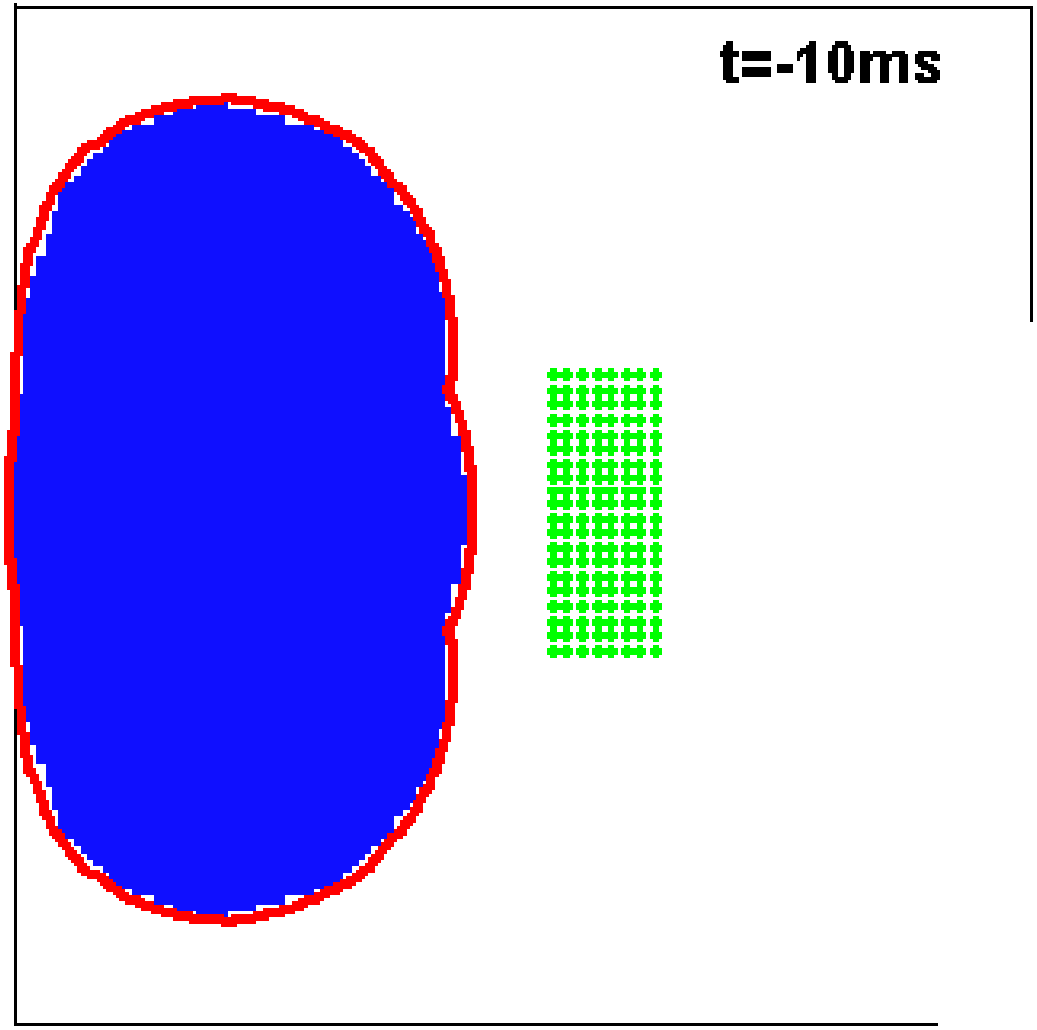


钨合金棒对钢板冲击

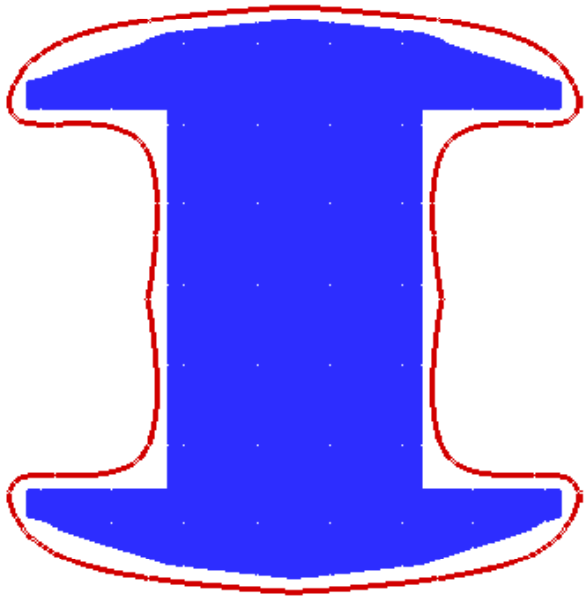
E. P. Fahrenthold等



无网格法的应用

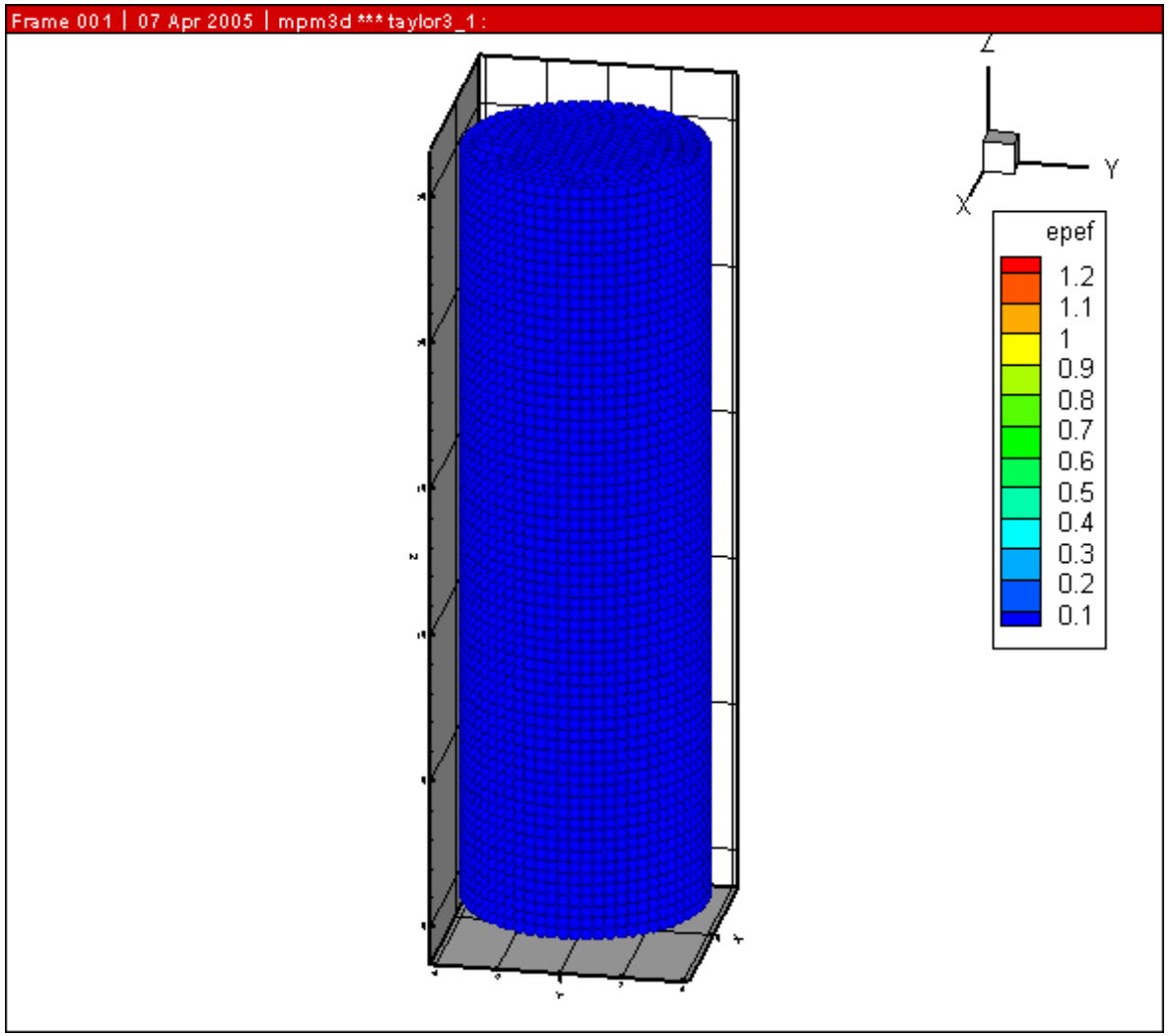


MPM



无网格法的应用

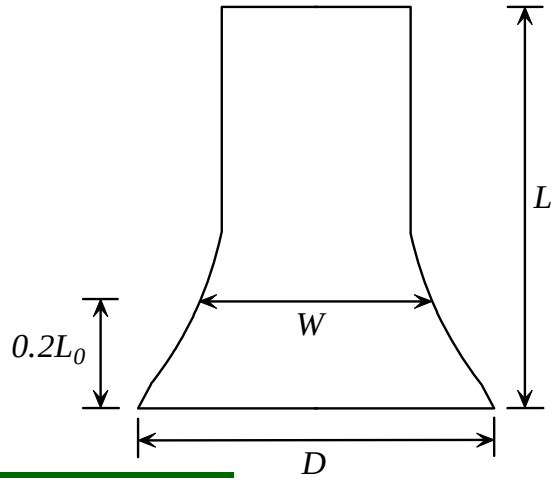
Taylor杆



MPM

无网格法的应用

误差定义：$\bar{\Delta} = \frac{1}{3}\left(\frac{|\Delta L|}{L_t} + \frac{|\Delta D|}{D_t} + \frac{|\Delta W|}{W_t}\right)$



	L (mm)	D (mm)	W (mm)	
Test*	16.2	13.5	10.1	-
FEM	16.3	13.4	10.0	0.008
MPM	16.4	13.6	9.9	0.011

	最大时间步长（ms）	最小时间步长（ms）	时间步	相对耗时
FEM	7.37E-5	1.45E-5	4657	13.4
MPM	1.96E-4	1.96E-4	408	1

*: Johnson et al. 1988 Journal of Applied Physics 64:3901-3910

无网格法的应用

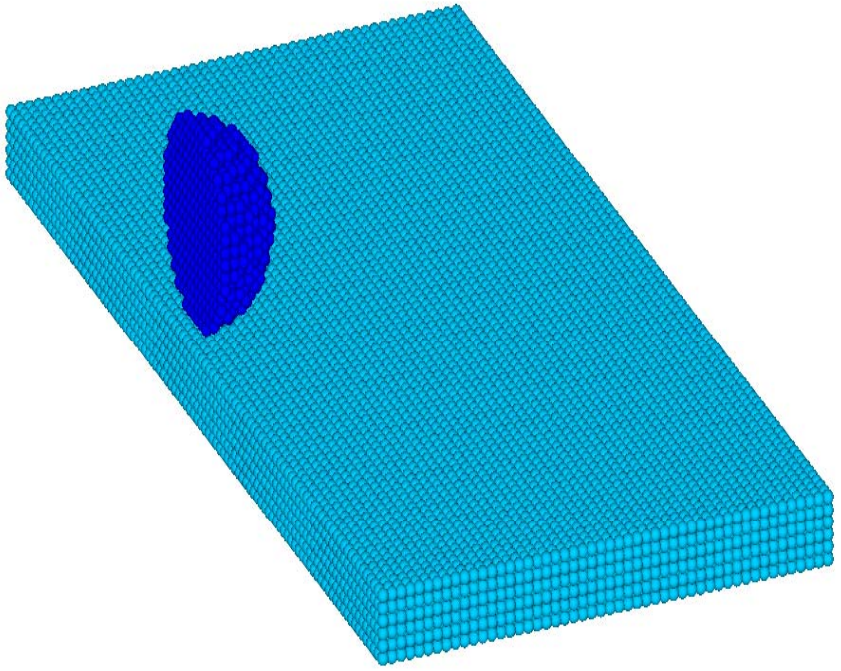
弹丸超高速碰撞薄板

弹丸直径: 8 mm

靶板厚度: 3 mm

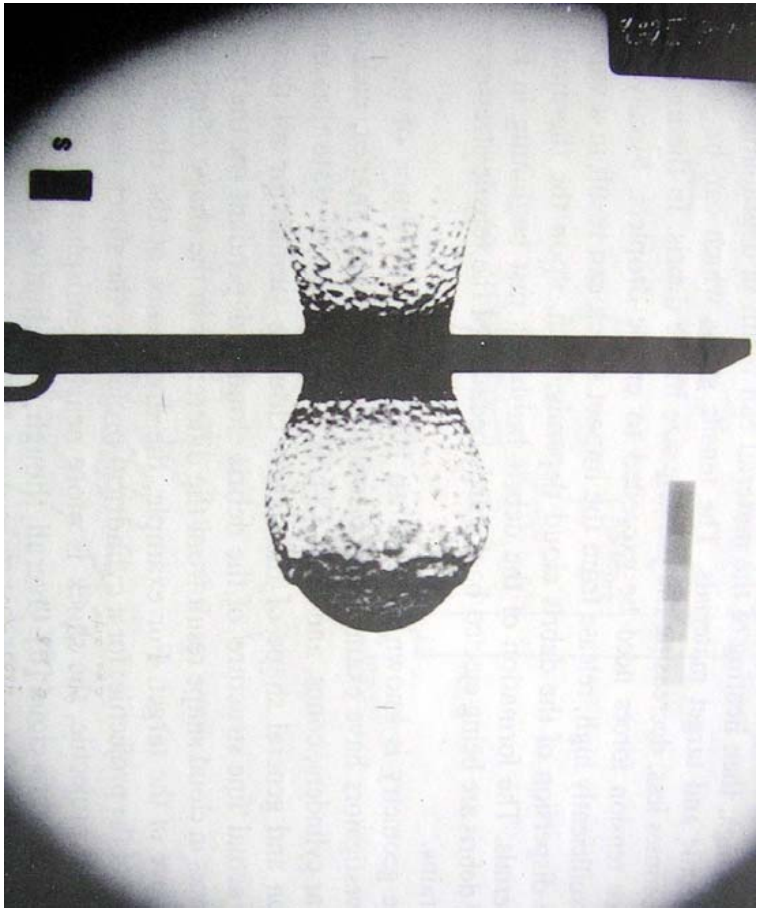
初速度: 6.6 km/s

37,142 物质点

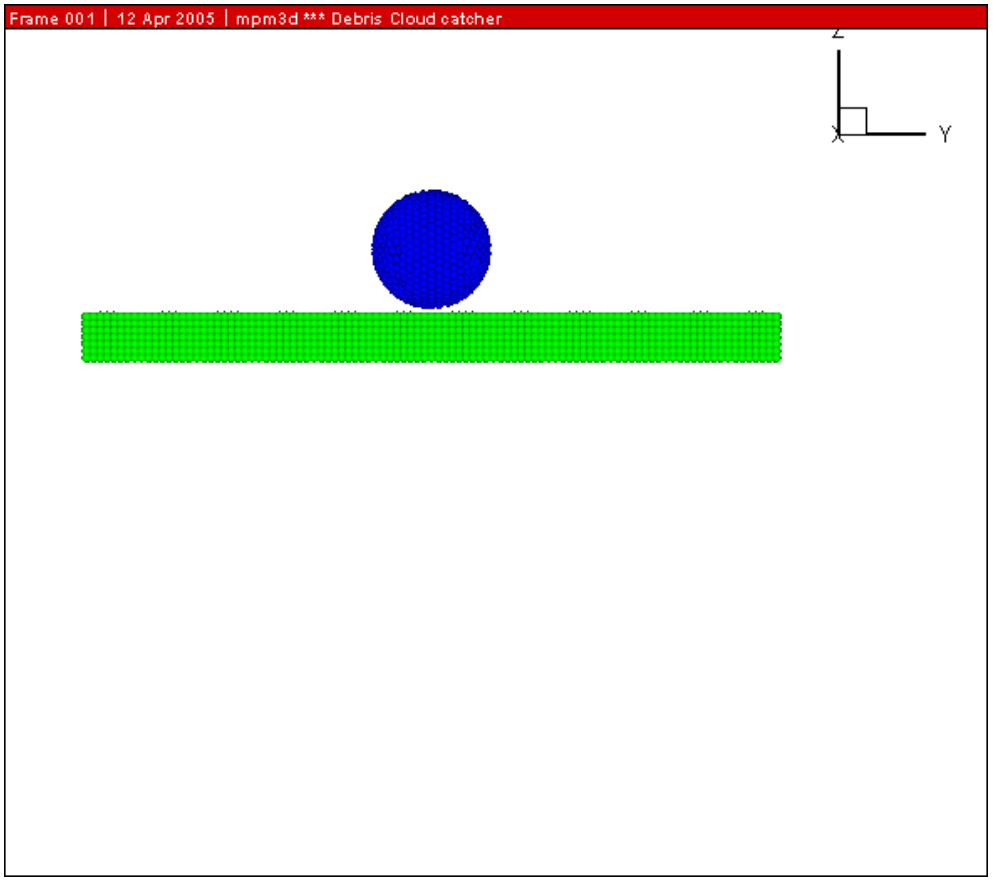


无网格法的应用

弹丸超高速碰撞薄板



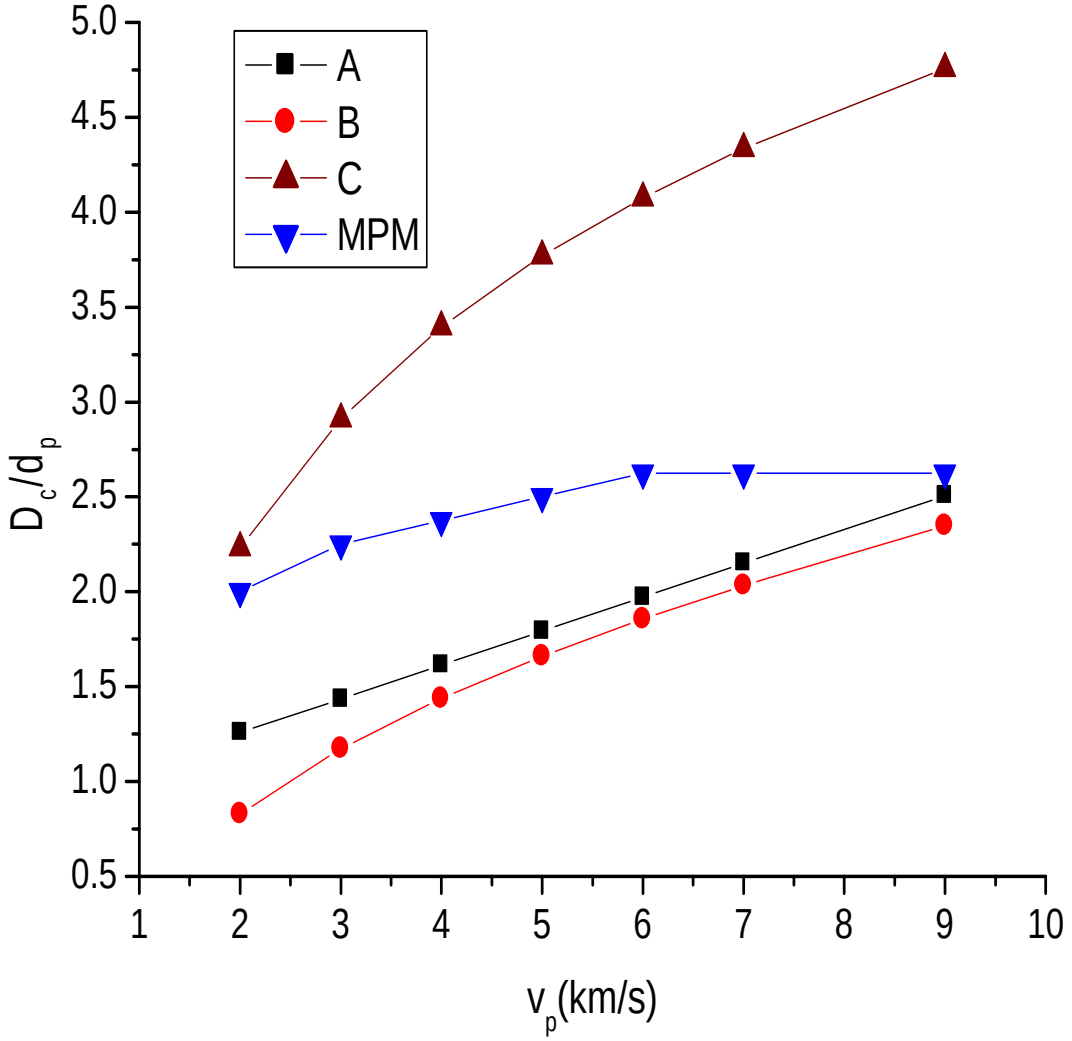
Anderson et al. 1990, Int. J. Impact Engng 9(1):89-113



时间： 9 微秒

无网格法的应用

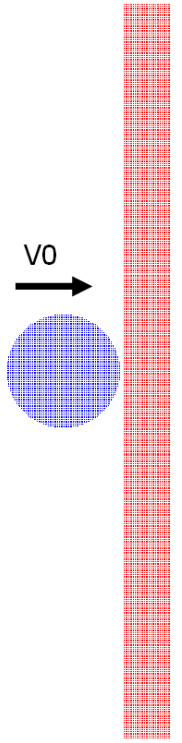
不同弹速下的穿孔特征



Numerical examples

Debris cloud

- Projectile: Lead sphere, r =7.5mm, m = 20g
- Target : Lead plate, t = 6.35 mm
- Impact velocity: v_0 = 6.58 km/s
- Material model
  - Elastic-plastic constitutive model
  - Mie-Grüneisen EOS
- Material failure model
  - Tensile Failure ($P_{\min}$ = –1500 MPa)
  - Plastic Strain Failure ($\varepsilon_{p\max}$= 3.0)

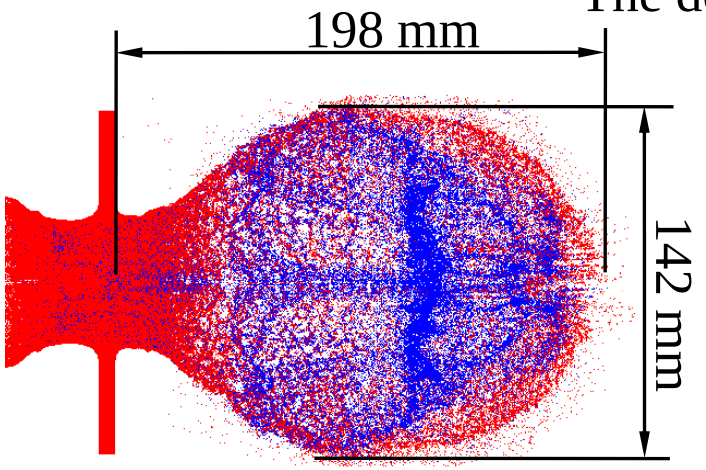


Pb to Pb

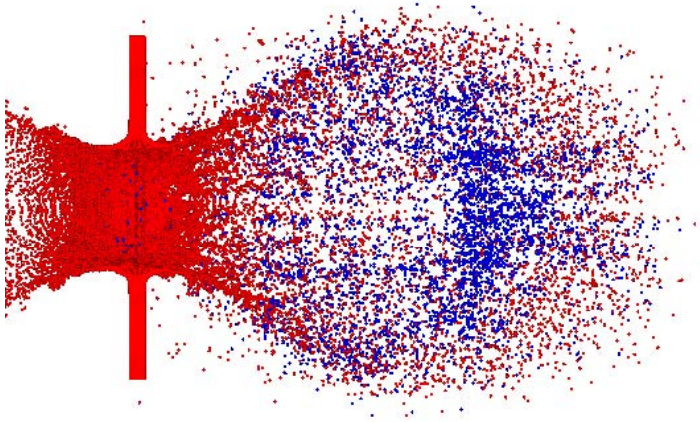
Numerical examples

Debris cloud

The debris cloud at 30.6 μs



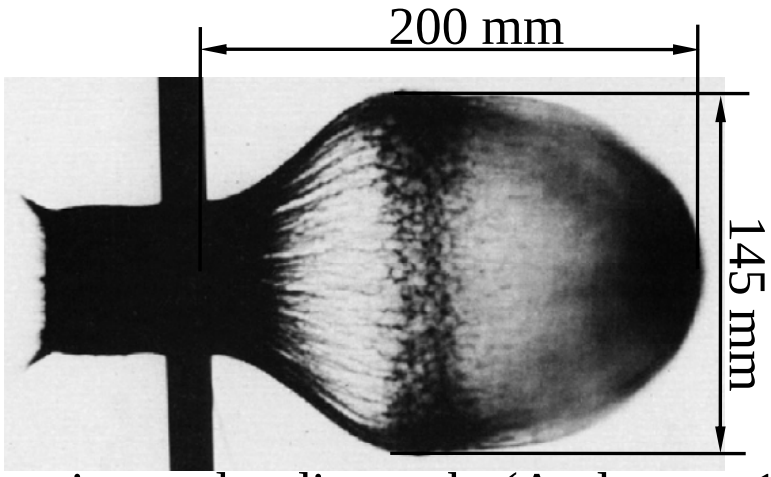
13,542,030 particles



847,888 particles

2 Quad-Core Xeon 2.66 GHz processors

1.93 hours

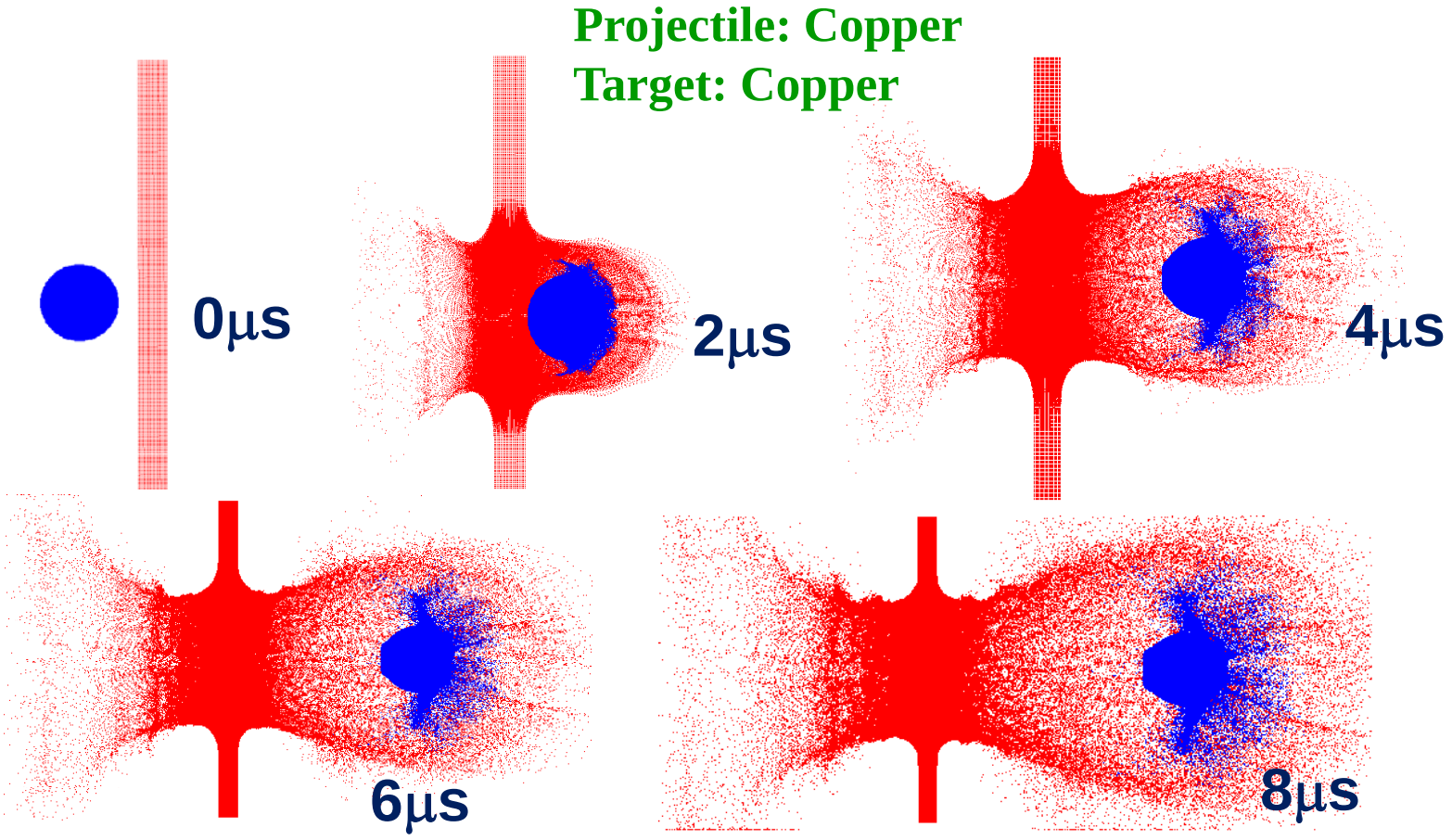


Experimental radiograph (Anderson, 1990)

Numerical examples

Debris cloud

- 4,462,360 particles
- 22,664,961 grid nodes (200 × 200 × 560 cell)



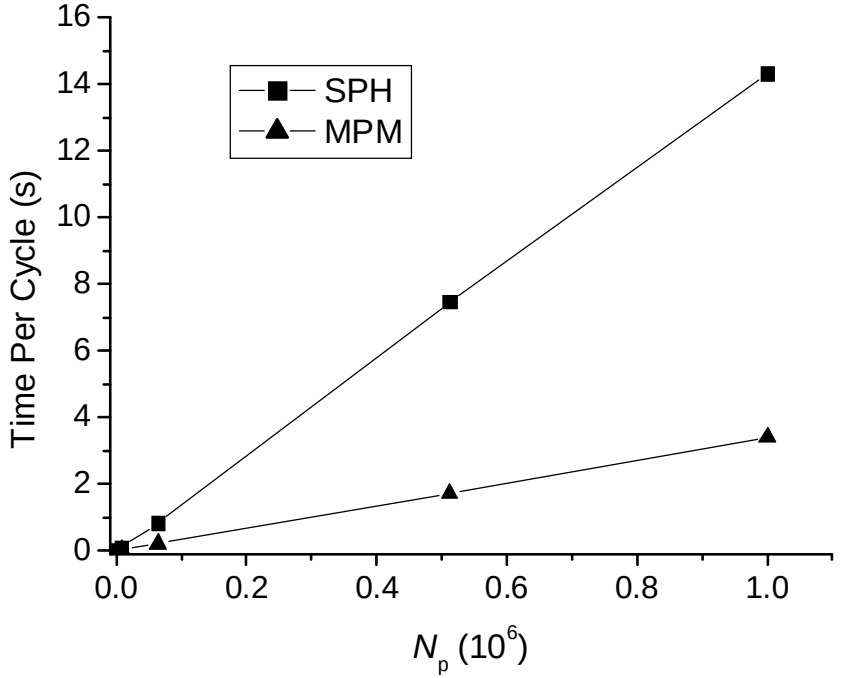
数值算例 MPM与SPH比较

质点总数	TPZC in SPH (10^{-9}s)	TPC in SPH (s)	TPZC in MPM (10^{-9}s)	TPC in MPM (s)
1000	4424	0.00442	2038	0.00204
8000	11061	0.08849	2445	0.01956
64000	12859	0.82298	3236	0.20710
512000	14587	7.46854	3362	1.72134
1000000	14310	14.3100	3401	3.40100

TPZC — 每个时间步每个质点所用的计算时间

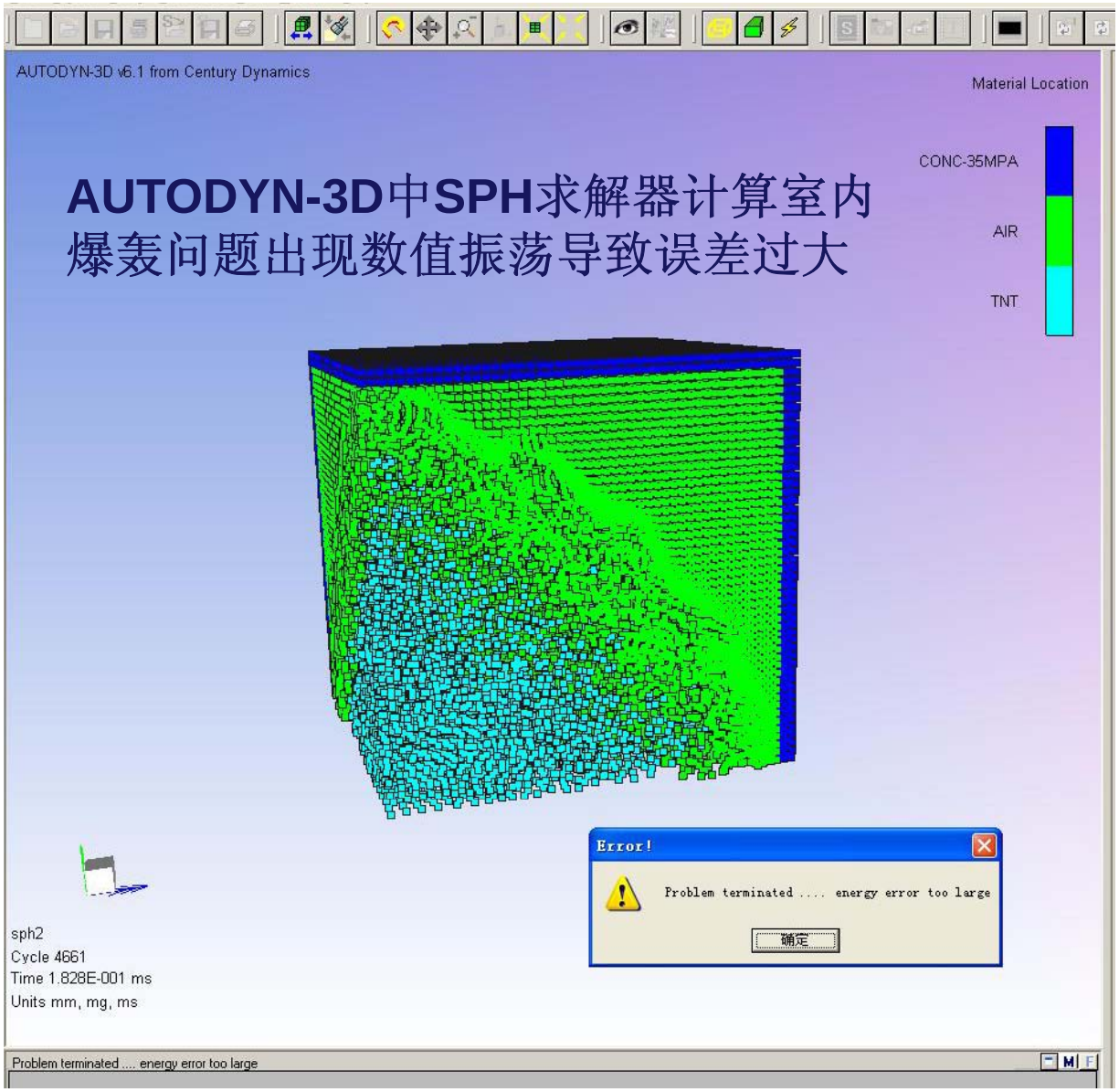
TPC — 每个时间步所用的时间

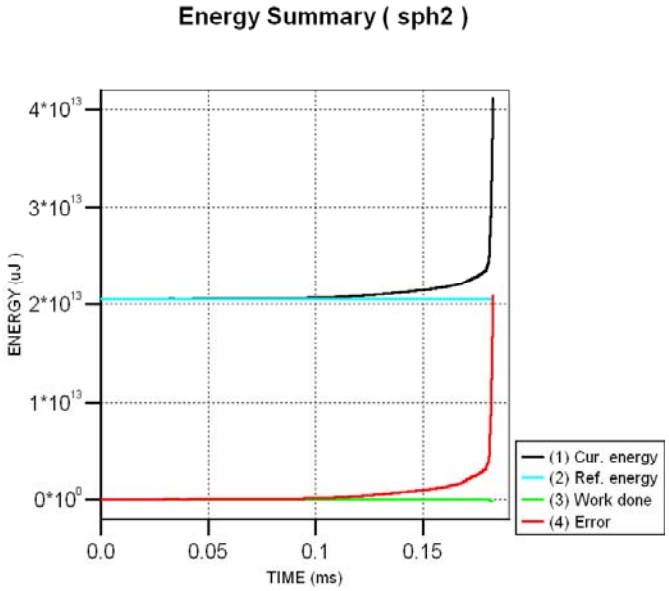
SPH计算由LS-DYNA程序完成

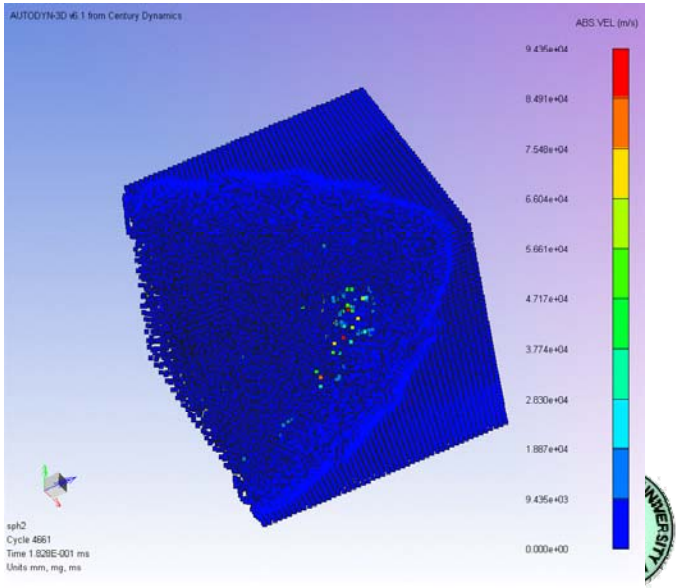


数值算例

MPM与SPH比较

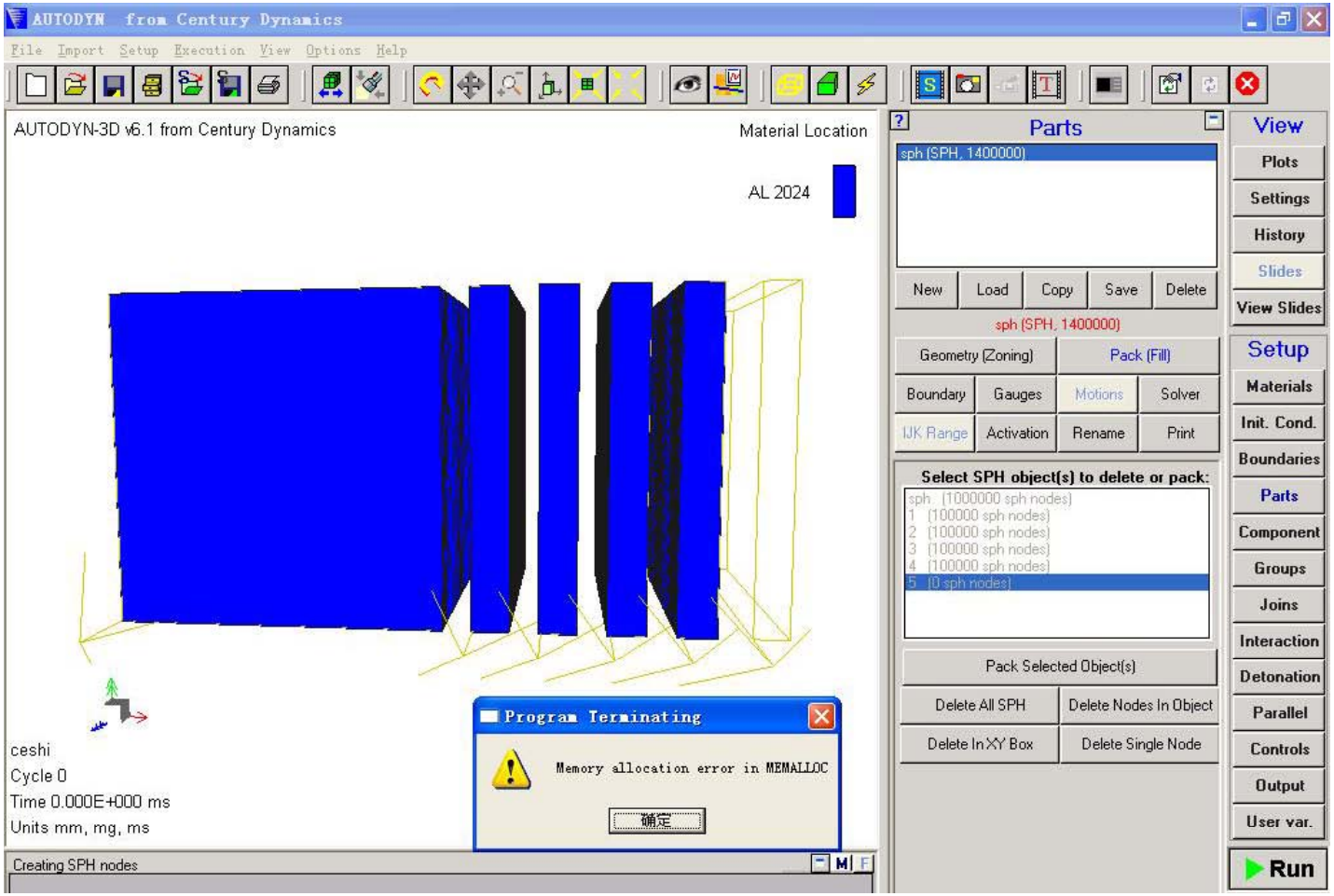






数值算例　　MPM与SPH比较

AUTODYN6.0中SPH粒子数不能超过150万(11.0版为200万)，否则内存出错



数值算例

MPM与SPH比较

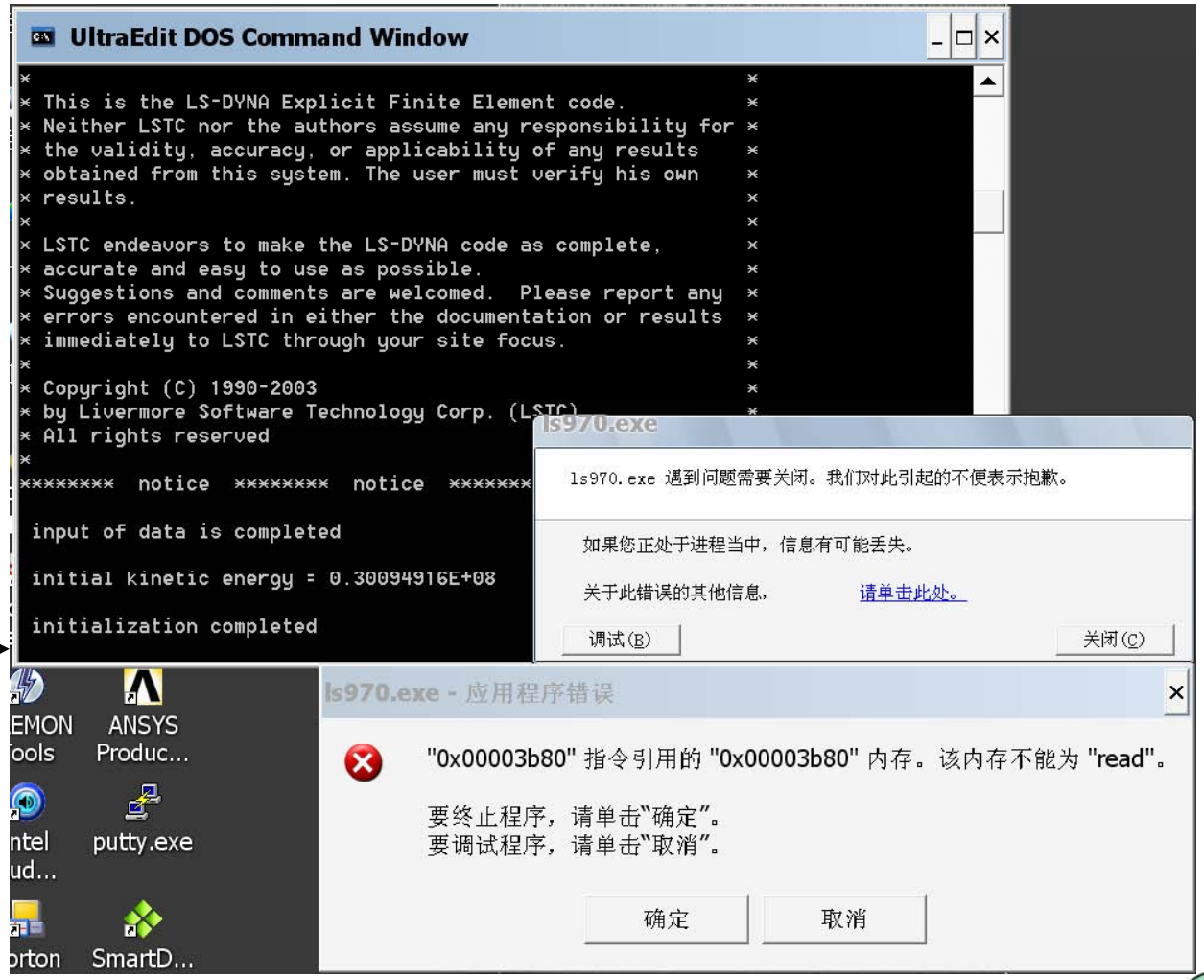


1,274,376 质点

SPH:

LS-DYNA
970.5434 出错

970s.6763.169
占用内存1.12G



数值算例

泰勒杆碰撞

误差 $\bar{\Delta} = \frac{1}{3}\left(\frac{|\Delta L|}{L_t} + \frac{|\Delta D|}{D_t} + \frac{|\Delta W|}{W_t}\right)$

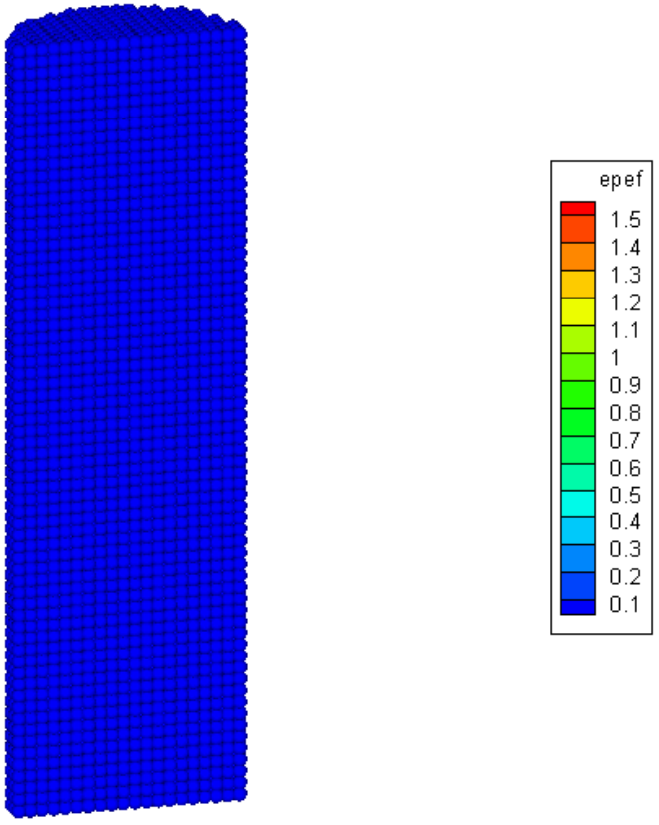
$L_0 = 25.4\text{mm}$ $D_0 = 7.6\text{mm}$

$v_0 = 190\,\text{m/s}$

SPH和MPM 的计算结果

	L (mm)	D (mm)	W (mm)	$\bar{\Delta}$
实验	16.2	13.5	10.1	-
SPH1	15.4	15.6	9.9	7.5%
SPH2	15.5	14.7	10.0	4.7%
MPM	16.3	13.0	9.6	3.1%
FEM	16.3	13.2	10.1	0.9%

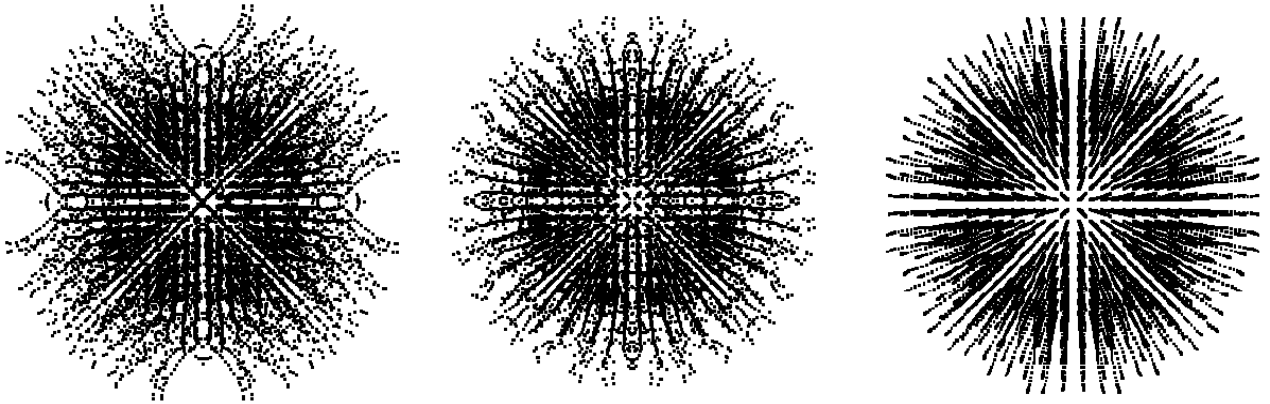
SPH1 — 光滑长度 = 1.2
SPH2 — 光滑长度 = 1.4
FEM — LS-DYNA3D



数值算例　　泰勒杆碰撞

SPH和MPM的计算量比较

	Δt_{max} (ns)	Δt_{min} (ns)	Steps	TPZC (μs)	CPU (s)
SPH1	120	118	672	12.088	172
SPH2	140	138	576	16.727	204
MPM	133	133	604	3.175	40
FEM	39.7	12.1	5482	1.052	116



SPH1　　SPH2　　MPM

泰勒杆的最终构型（俯视图）

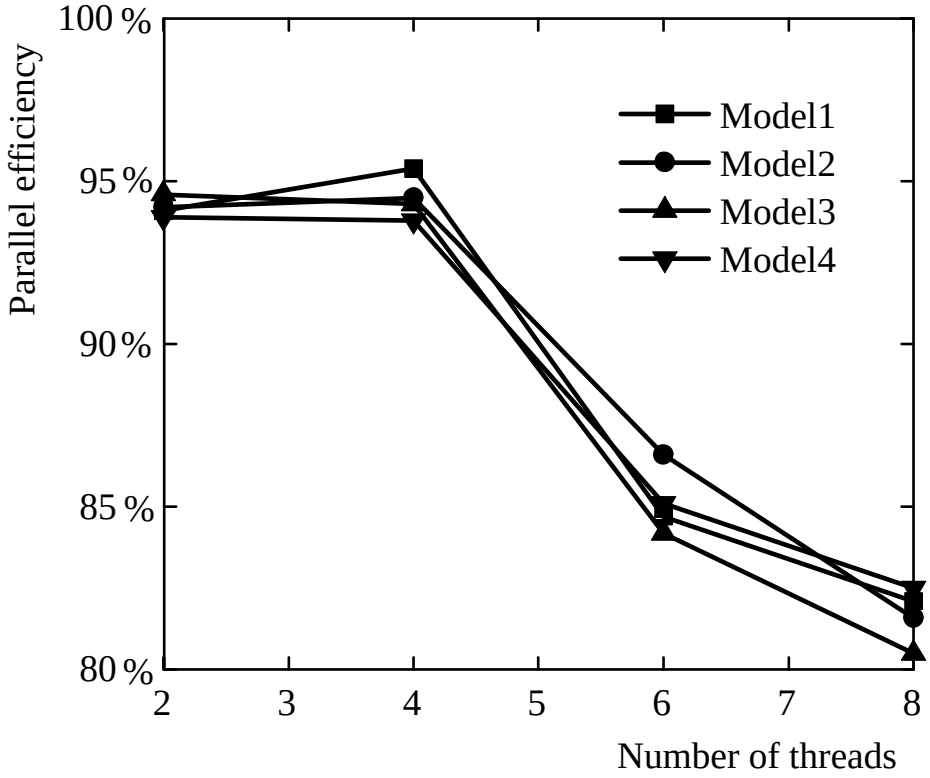
Numerical examples

Taylor bar impact

Parallel performance test

HP DL140G3 server

- **2 Quad-Core Intel Xeon 2.66GHz processors**
- **8 GB memory.**



Model 1: 56,056 particles

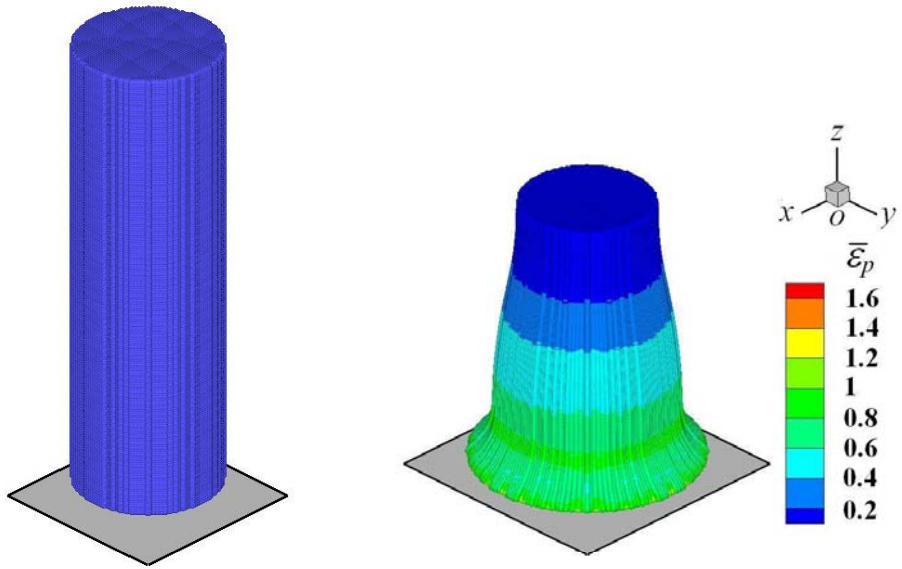
Model 2: 244,524 particles

Model 3: 1,155,192 particles

Model 4: 12,416,320 particles

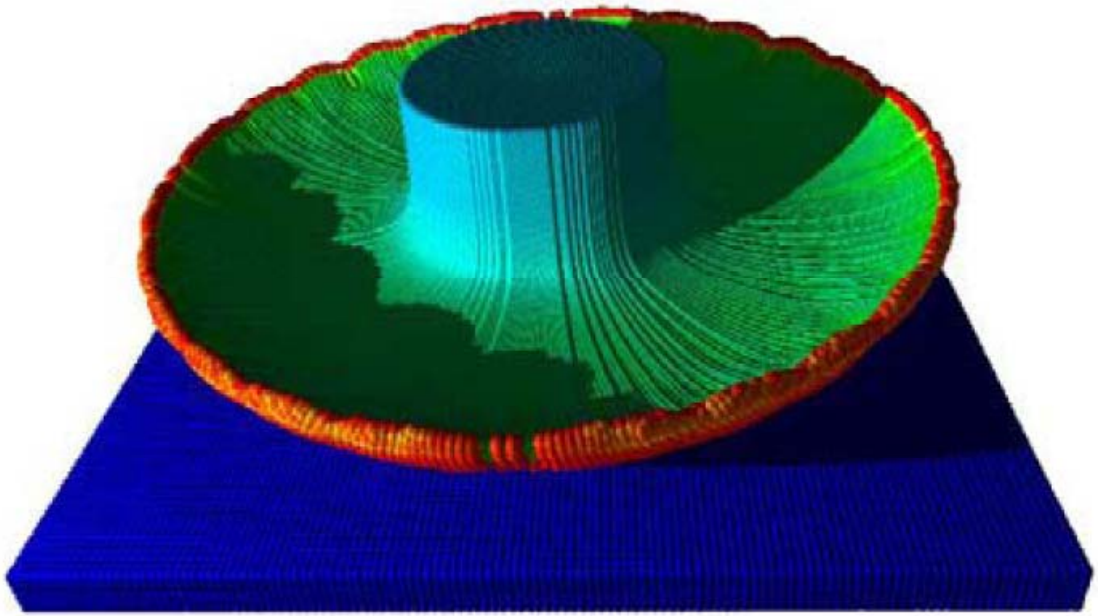
数值算例 泰勒杆碰撞

- 12,416,320 个质点
- 8,322,185 节点 (176 × 176 × 264 背景网格)
- 8核计算机上耗时10.7小时



Taylor bar impact

数值算例　　泰勒杆碰撞



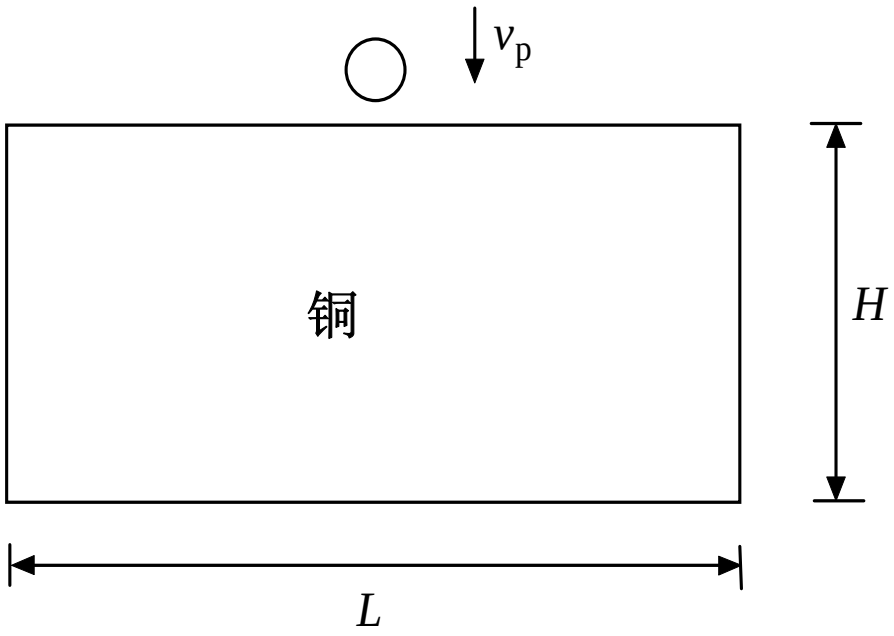
MPM计算采用了不同的塑性模型，如Johnson-Cook模型和MTS模型，并将计算结果与试验进行了对比。

美国犹他大学火灾和爆炸仿真中心

数值算例

成坑过程

- 碰撞速度：6.0 公里/秒
- 弹丸质量：0.5 克
- L = 80mm, H = 40mm
- **1,024,224** particles
- 在P4 2.8G PC机上耗时不到2小时
- 时间积分步长 = 46.2 微妙
- 时间步数: 692 步



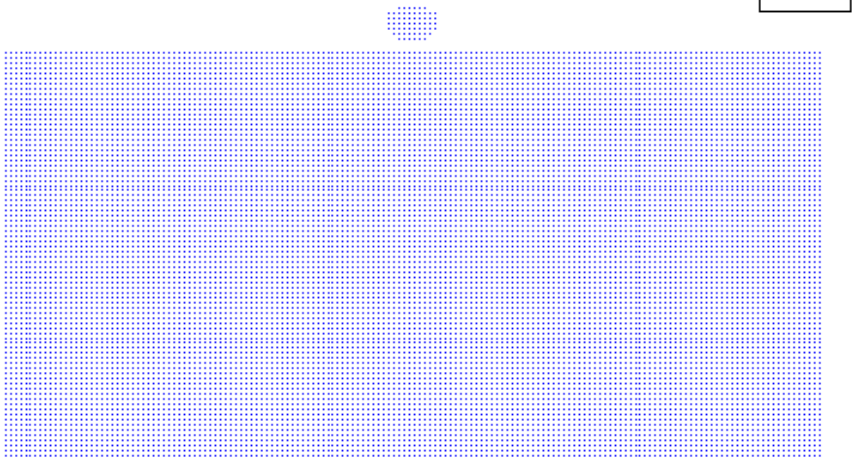
C.A. Wingate et. al.
International journal of impact engineering, 1993. 14: 819-830

数值算例

成坑过程

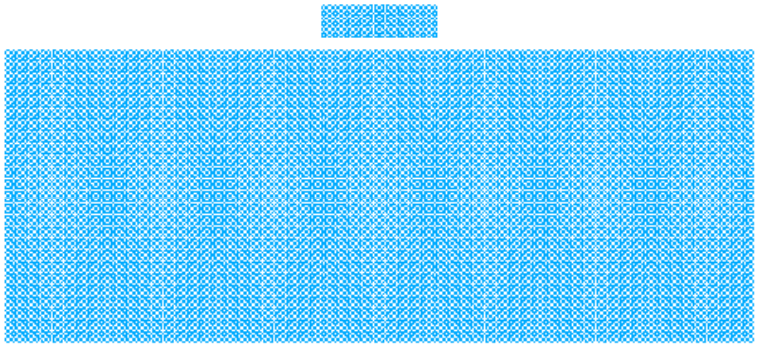
	坑深 (mm)	坑直径(mm)	深度/直径
实验*	14	25.4	0.55
EPIC	18	24	0.75
MESA	15.9	28	0.57
SPH	17.3	26	0.67
CALE	15.1	24.4	0.62
MPM3D	14	25	0.56

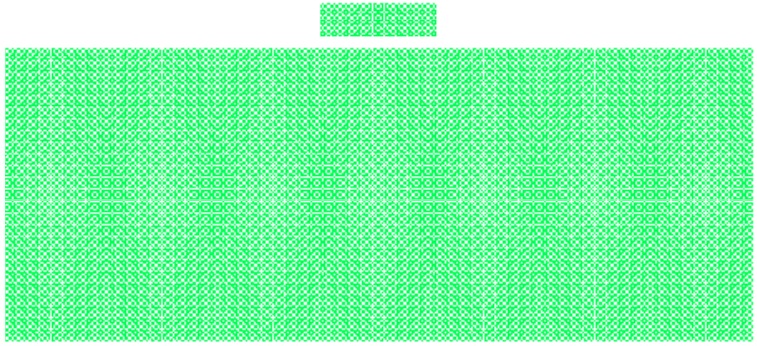
** Wingate, 1993*



数值算例

层裂过程





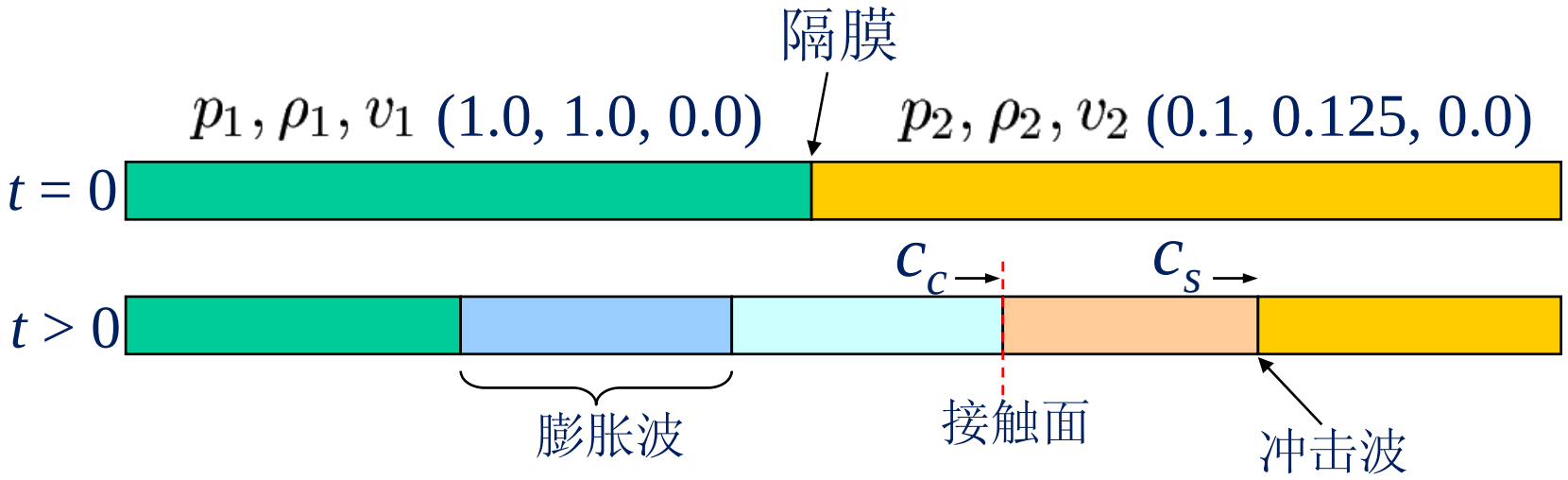
压力云图

拉格朗日有限元法难以有效模拟此问题

数值算例

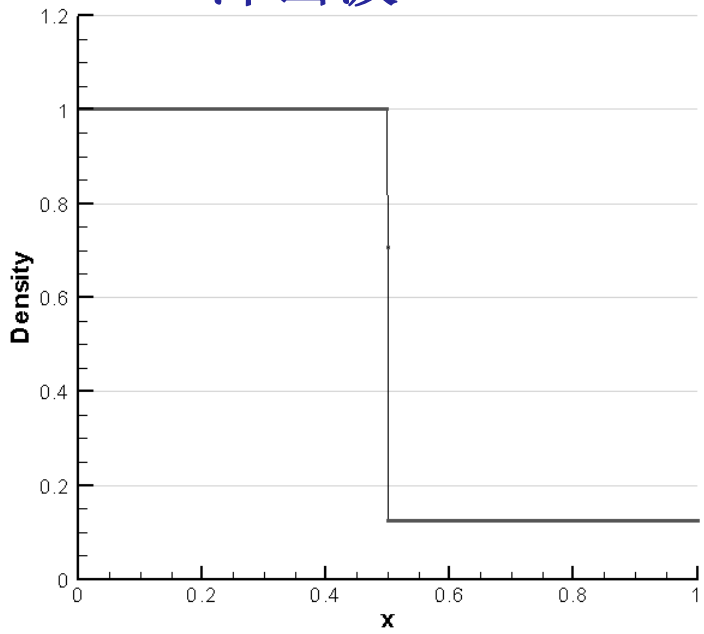
激波管

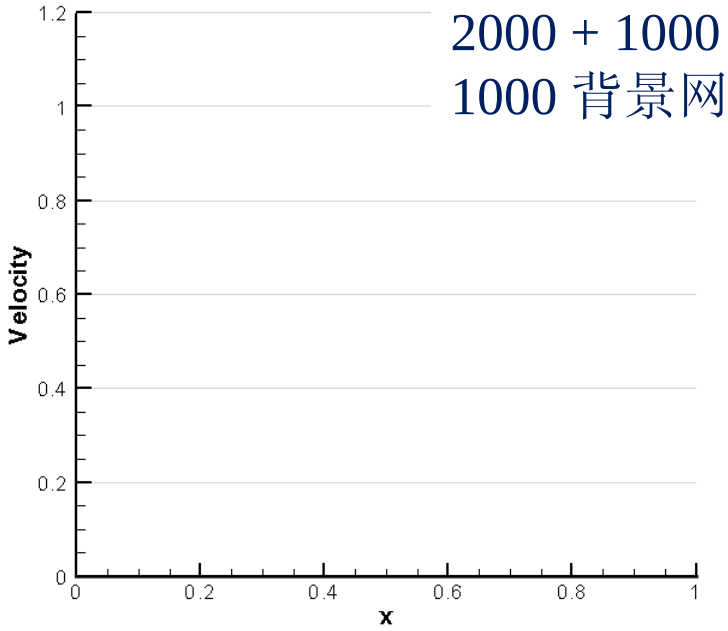
- 测试程序的可压缩流体分析能力
  - 强间断冲击波
  - 接触不连续

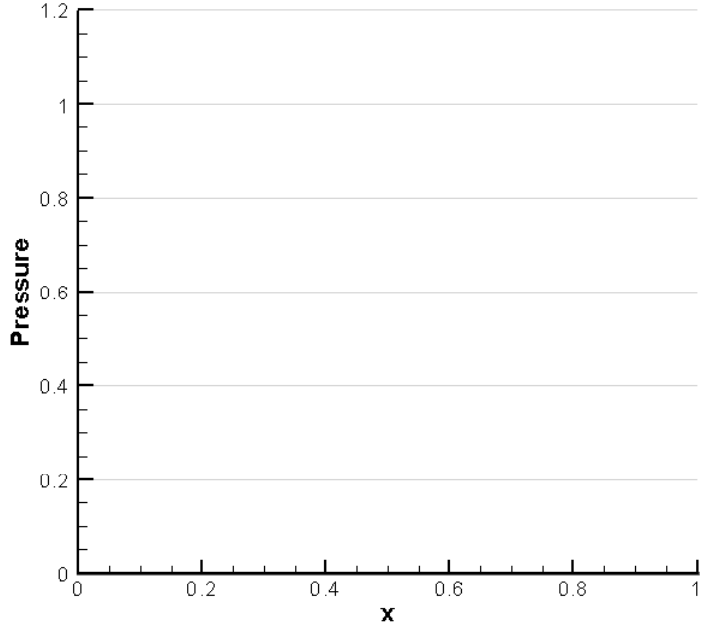


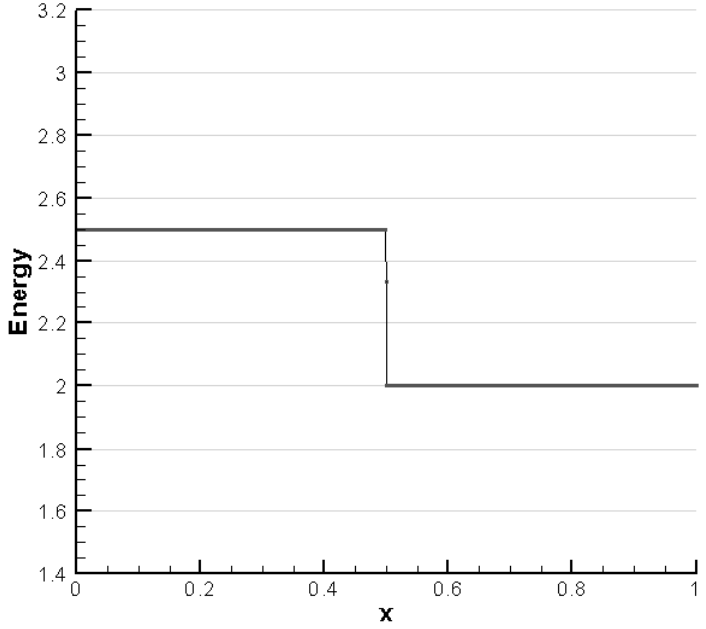
冲击波

MPM3D
2000 + 1000 质点
1000 背景网格









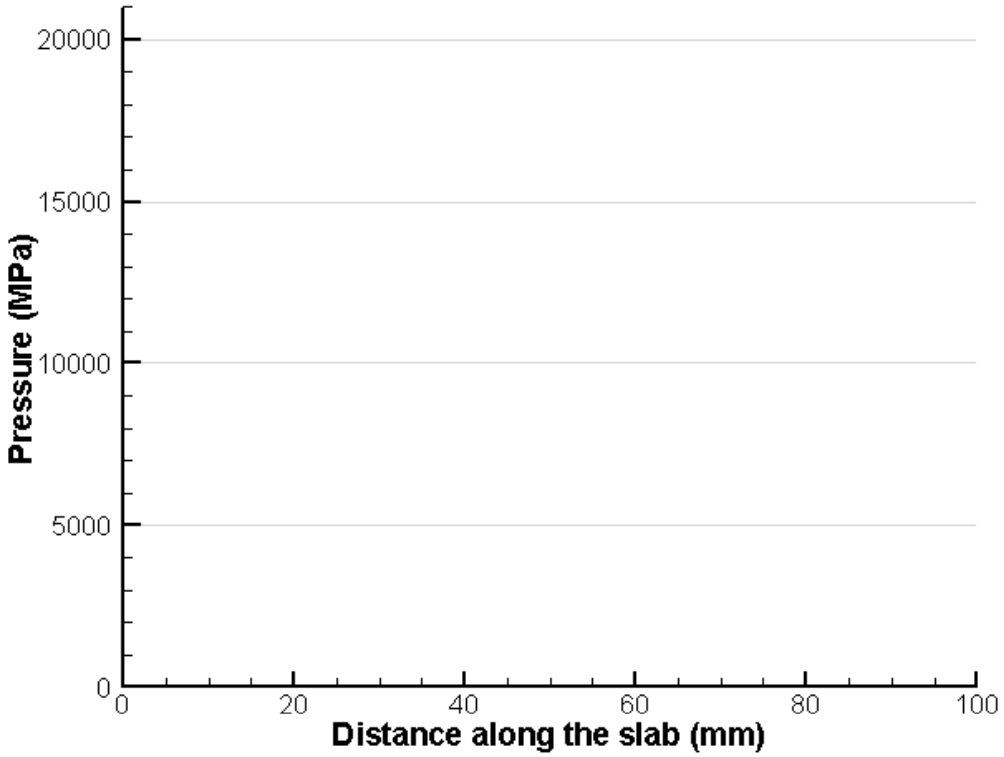
数值算例 一维TNT爆轰

药柱长度: 0.1m

MPM3D: 1000 质点,
500 背景网格

爆速: 6930m/s

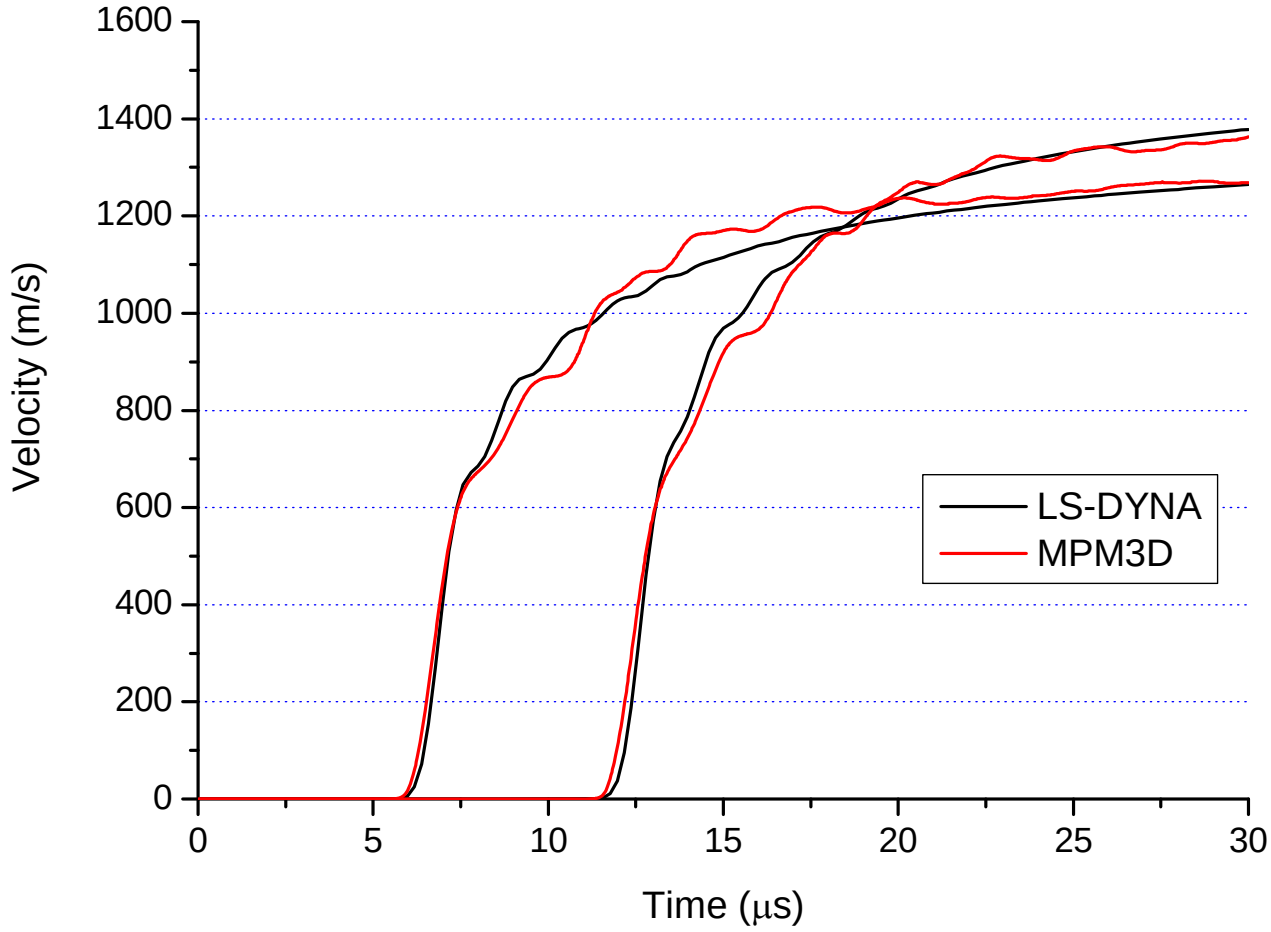
JWL 状态方程



Numerical examples

Cylinder expansion test

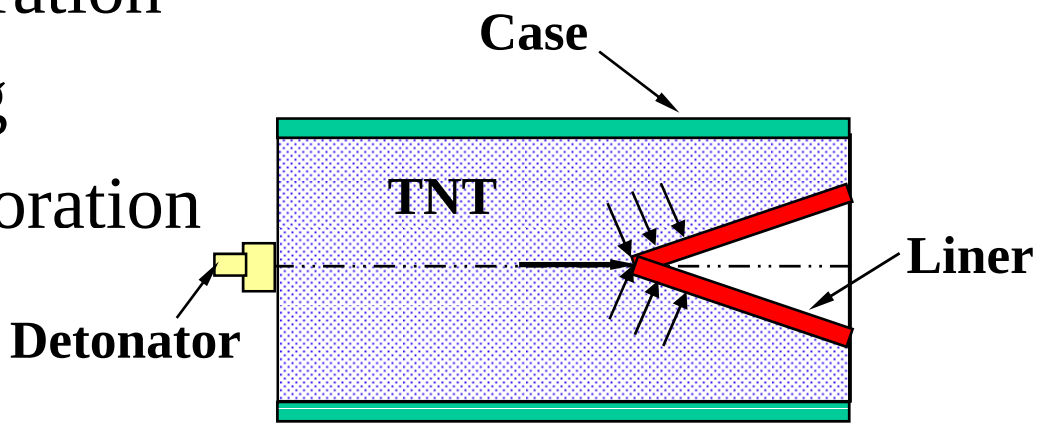




Numerical examples

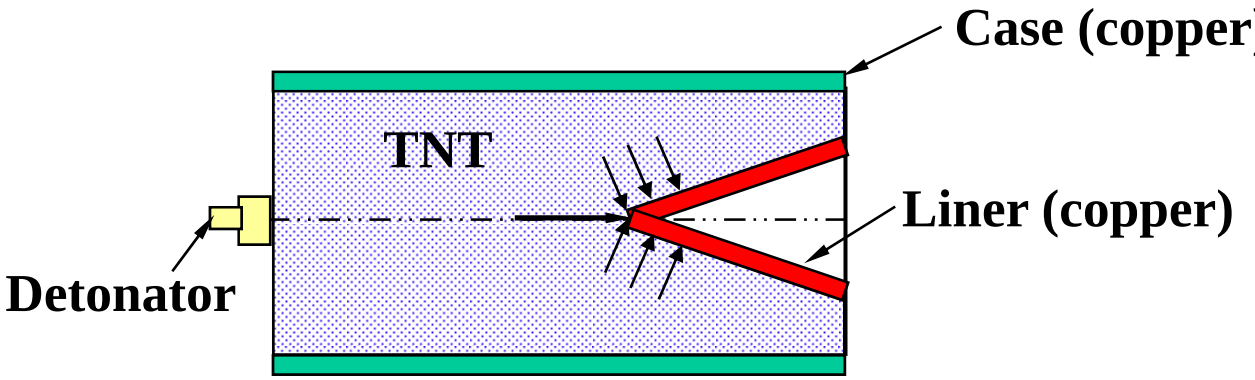
Shaped charge

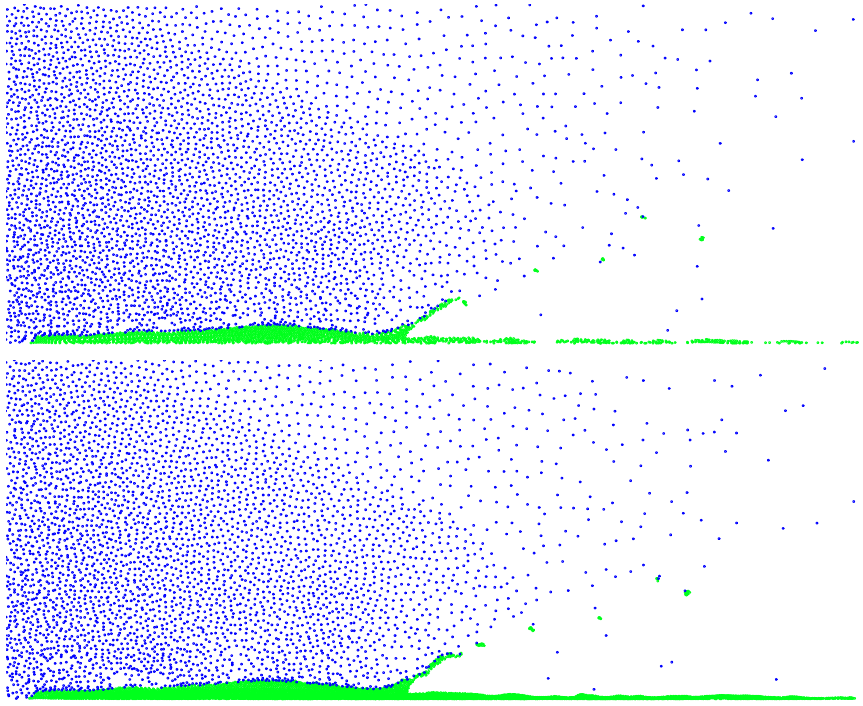
- Shaped charge
  - A cylinder of high explosive with a cone-shape thin metal liner in one end
  - Intense pressure → Collapse of the liner → A extreme high velocity jet (> 10 km/s)
- Application
  - Armor penetration
  - Metal cutting
  - Oil well perforation



Numerical examples

Shaped charge





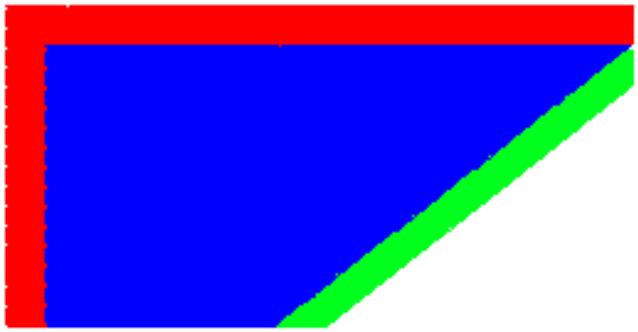
MPM

AMPM

30 μs

Numerical examples

Shaped charge



Numerical examples

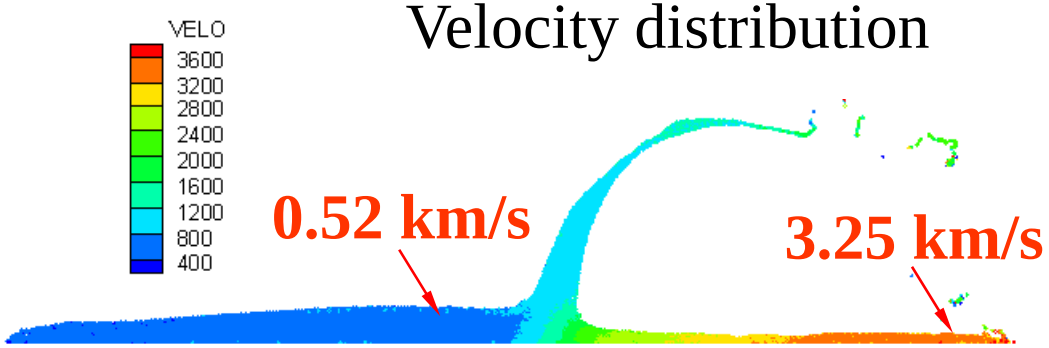
Shaped charge

Theoretical estimation
(Birkhoff's theory)

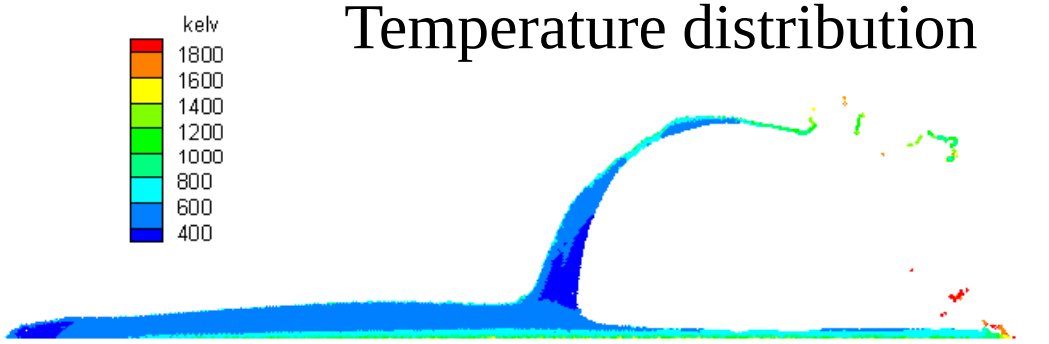
v_s = **0.58 km/s**

v_i = **3.66 km/s**

Velocity distribution



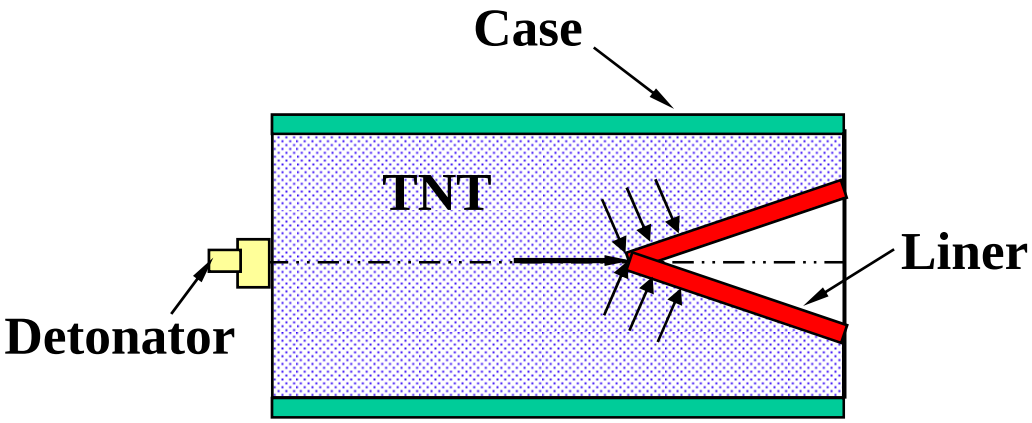
Temperature distribution



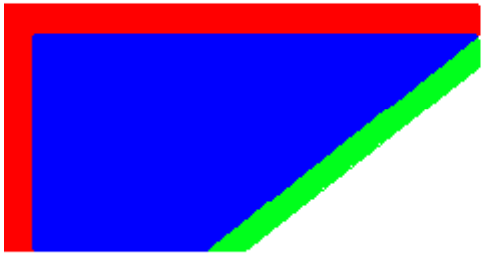
21 μs

Numerical examples

Shaped charge





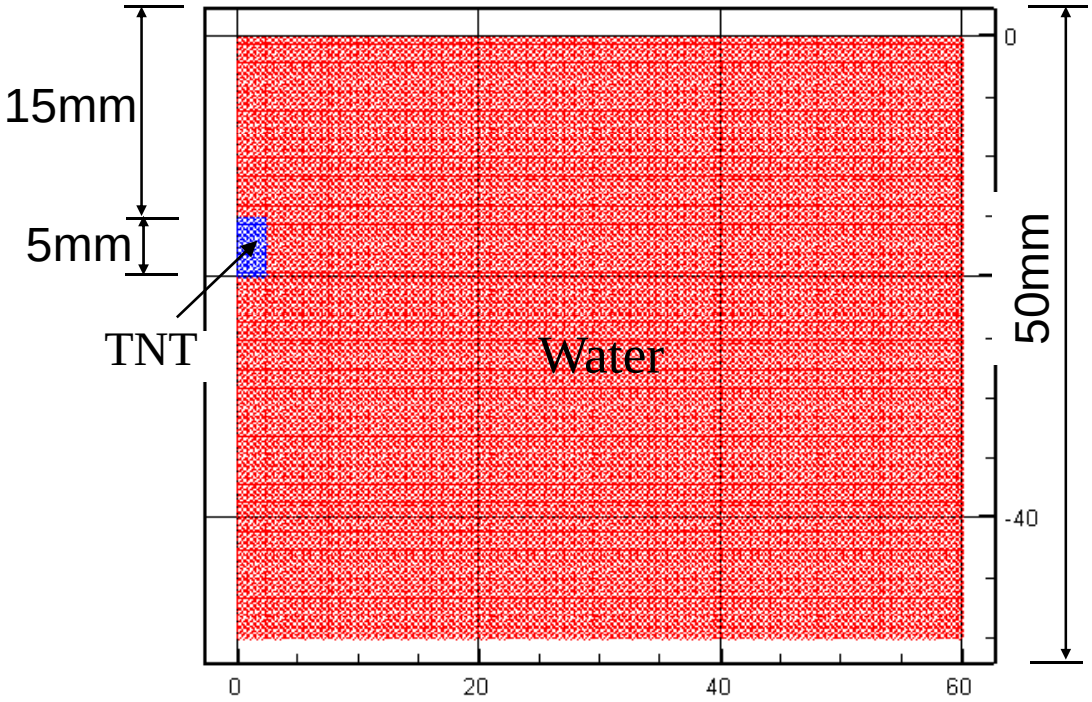




数值算例

水下爆炸

48600 质点

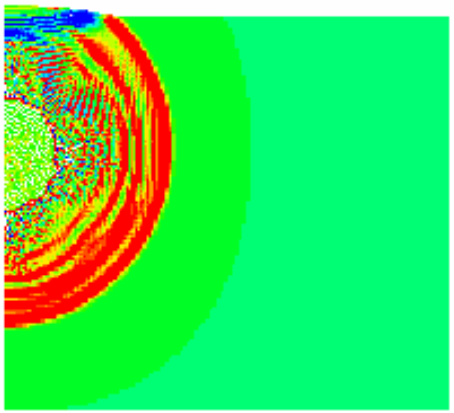




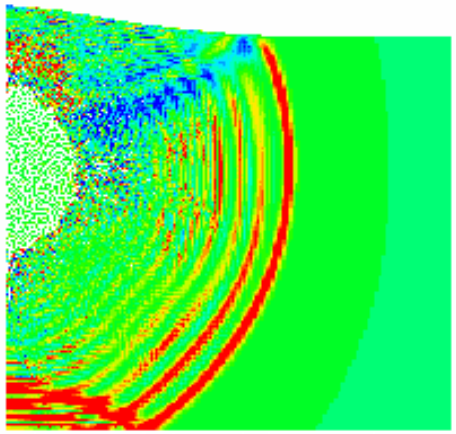
数值算例

水下爆炸

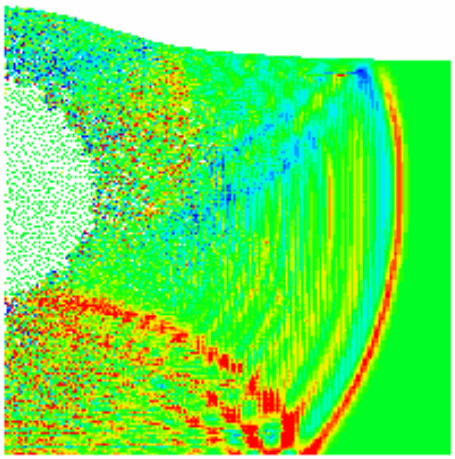




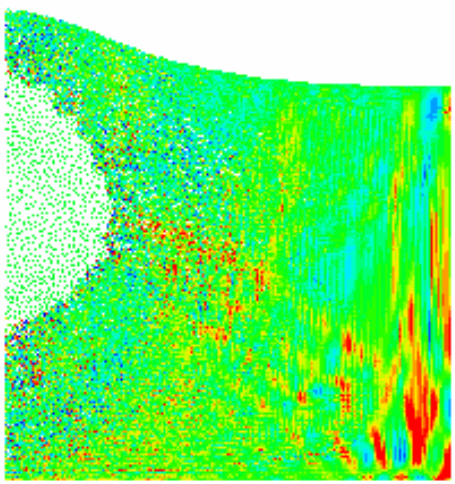
8us



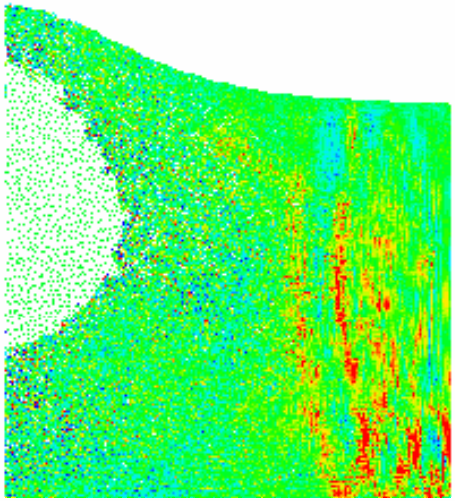
16us



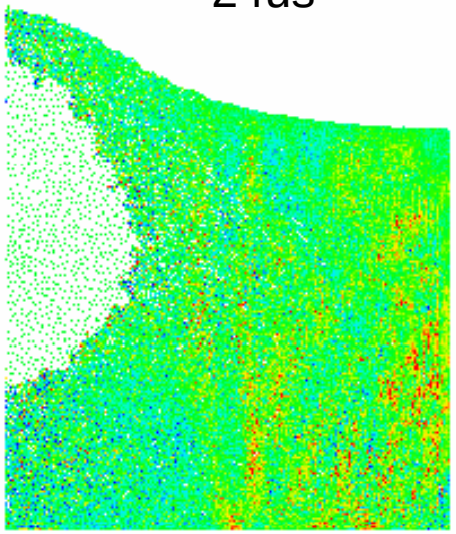
24us



32us

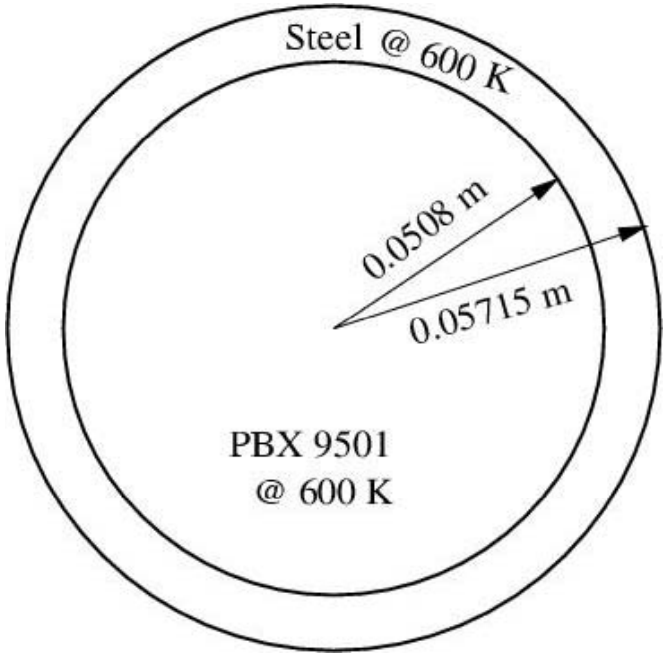


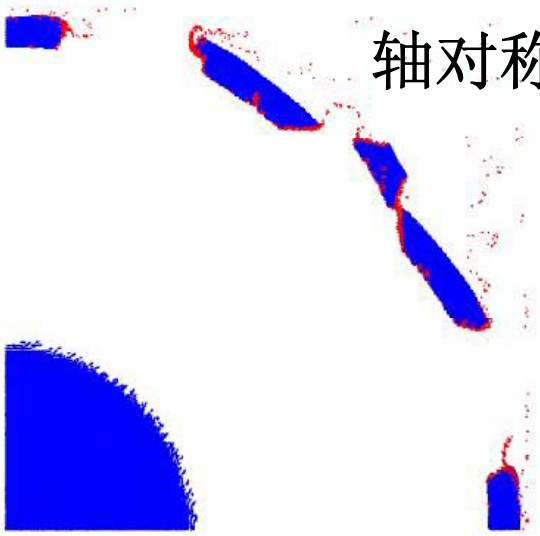
40us



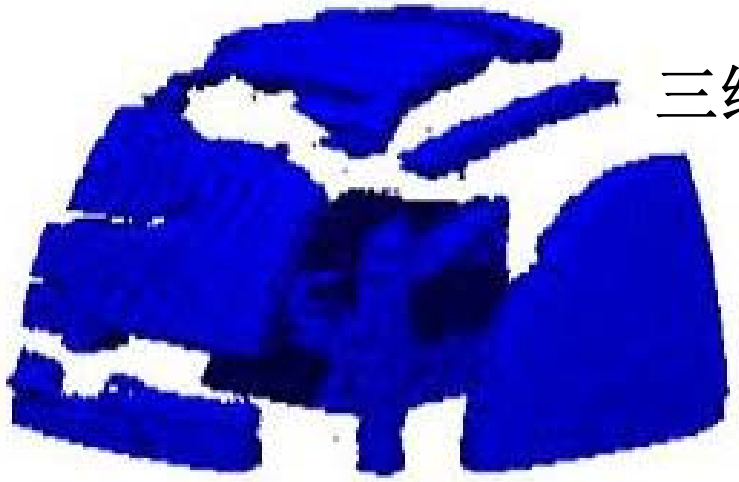
48us

数值算例　　爆炸下钢壳破坏





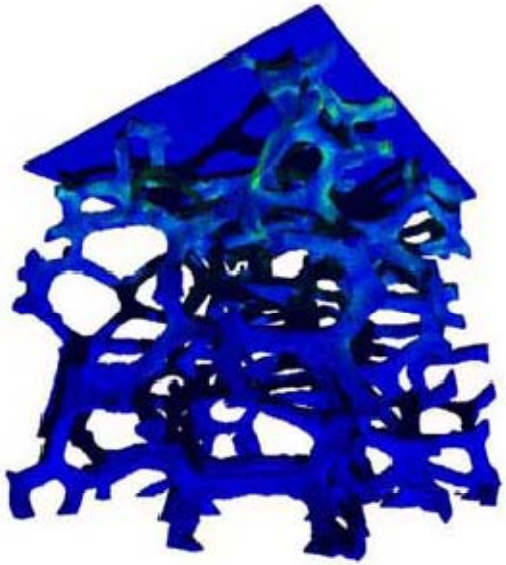
轴对称计算

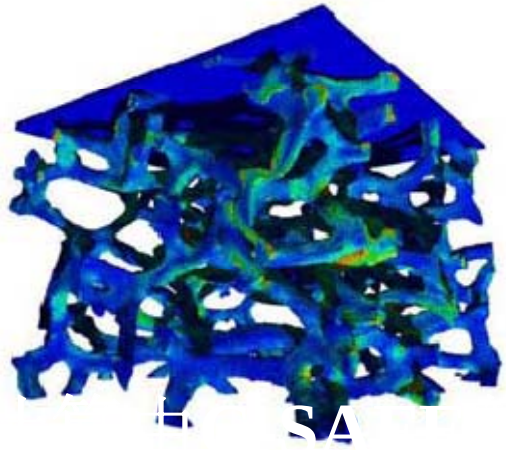


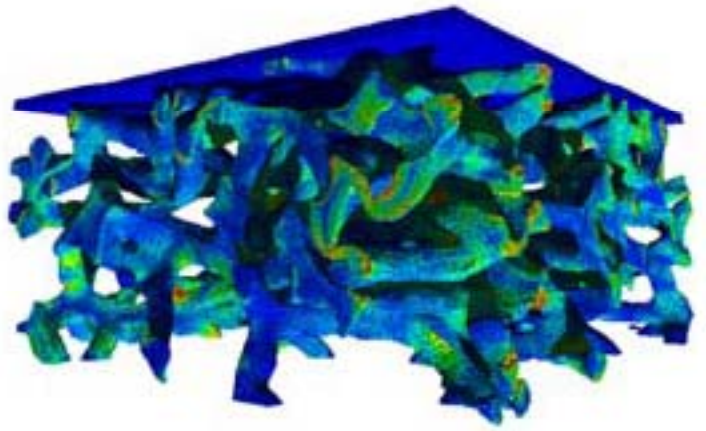
三维计算

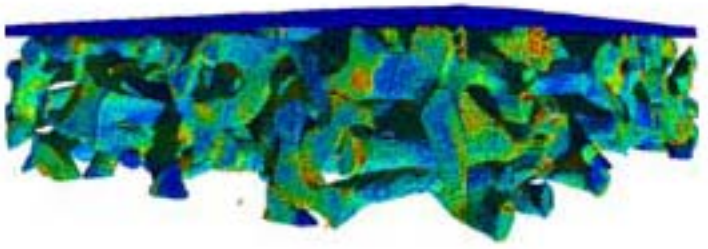
美国犹他大学
火灾和爆炸仿真中心

数值算例　　泡沫材料的压缩模拟









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