# 微细机械切削加工研究进展

## 第三届先进制造大会报告

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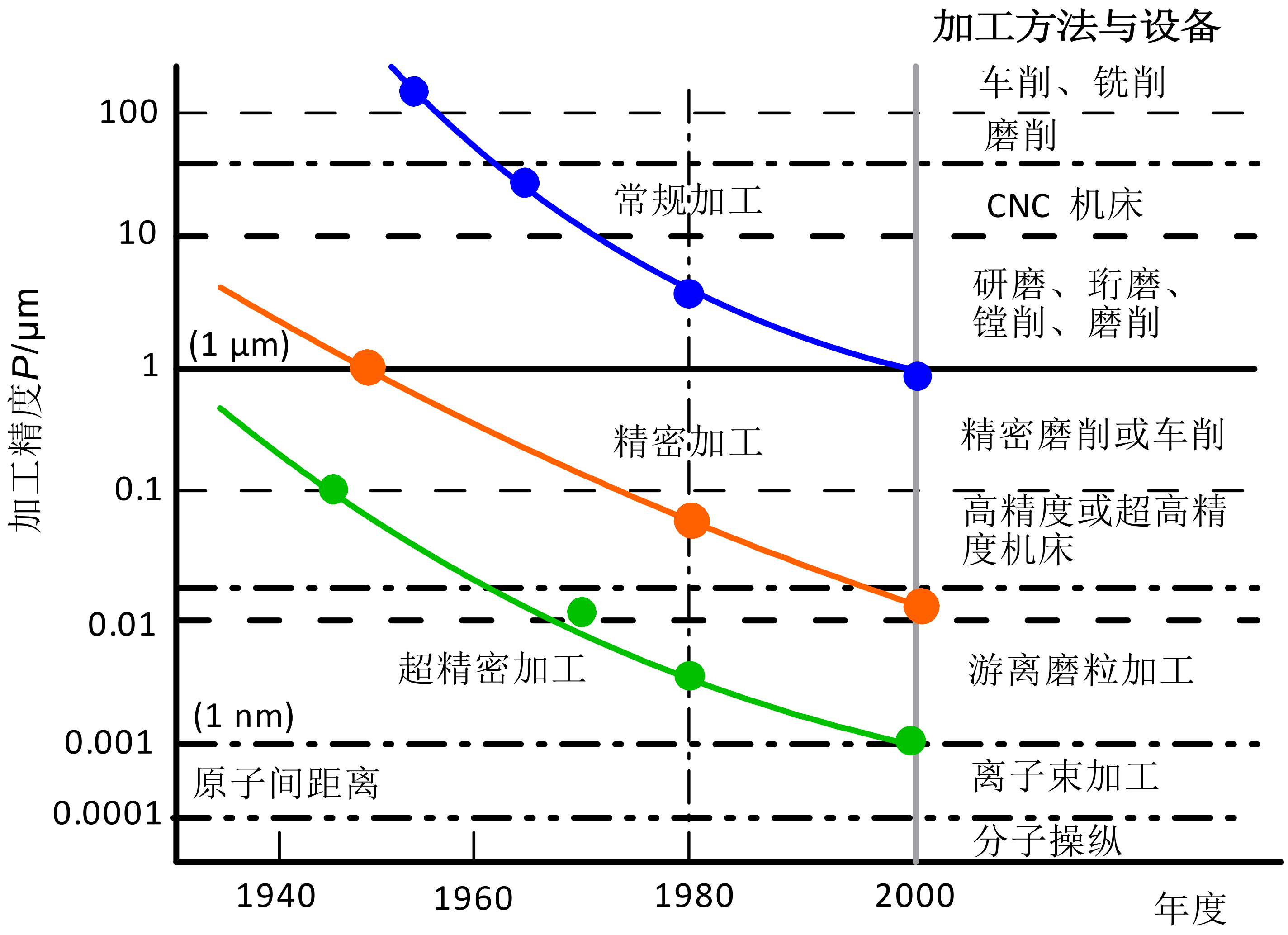
# 内 容

- 精密超精密加工
- 微切削加工
  - 定义及特点
- 微切削与宏观切削区别
  - 尺寸效应
- 研究实例

# 1. 精密与超精密加工




加工精度的发展

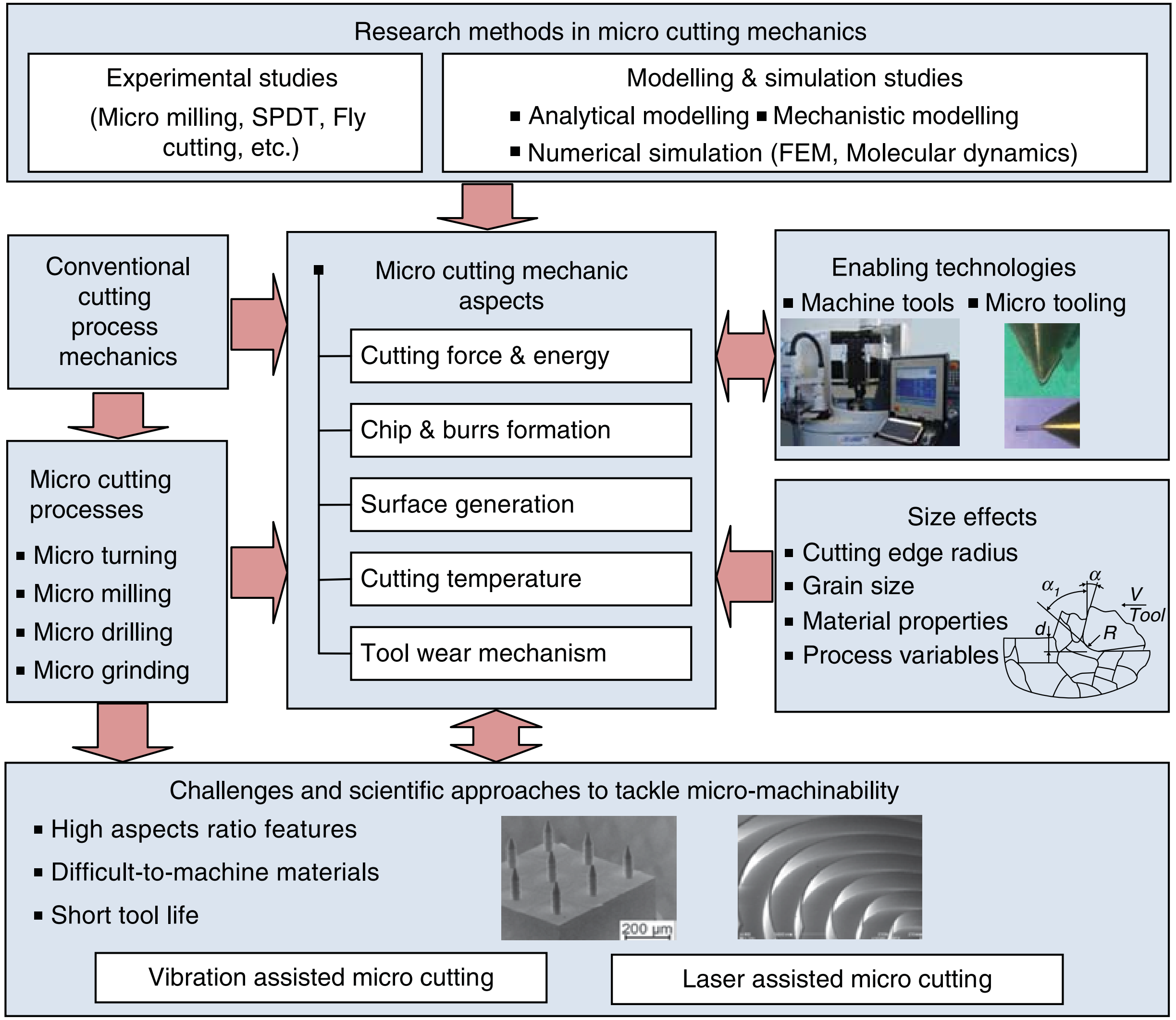
# 微切削加工与超精密加工

| | Micro cutting | Ultra-precision machining |
|---|---|---|
| Processes | Micro turning, milling, drilling, grinding, etc. | Single point diamond turning, fly cutting, etc. |
| Tooling | Various tooling materials: (coated) tungsten carbide, CVD, CBN, diamond tools | Natural diamond tools |
| Component size | 1–1000 μm | 1 mm above, Can be very large |
| Shape | 3D shape with high aspect ratios and geometric complexity | Rotational parts, both spherical and aspheric surface, normally low aspect ratios. |
| Accuracy | Absolute: <10 μm<br>Relative: $10^{-2}$–$10^{-5}$ | Absolute: <1 μm<br>Relative: $10^{-5}$–$10^{-6}$ |
| Surface finish | <100 nm Ra | Typically <20 nm Ra |
| Machines | Precision machining centres, precision micro machines, ultra-precision turning machines | Ultra-precision turning machines |
| Applications | Various applications requiring micro components | Electro-optics |
| Depth of cut (uncut chip thickness) | 1–10 μm | 0.1 μm – 10 μm |

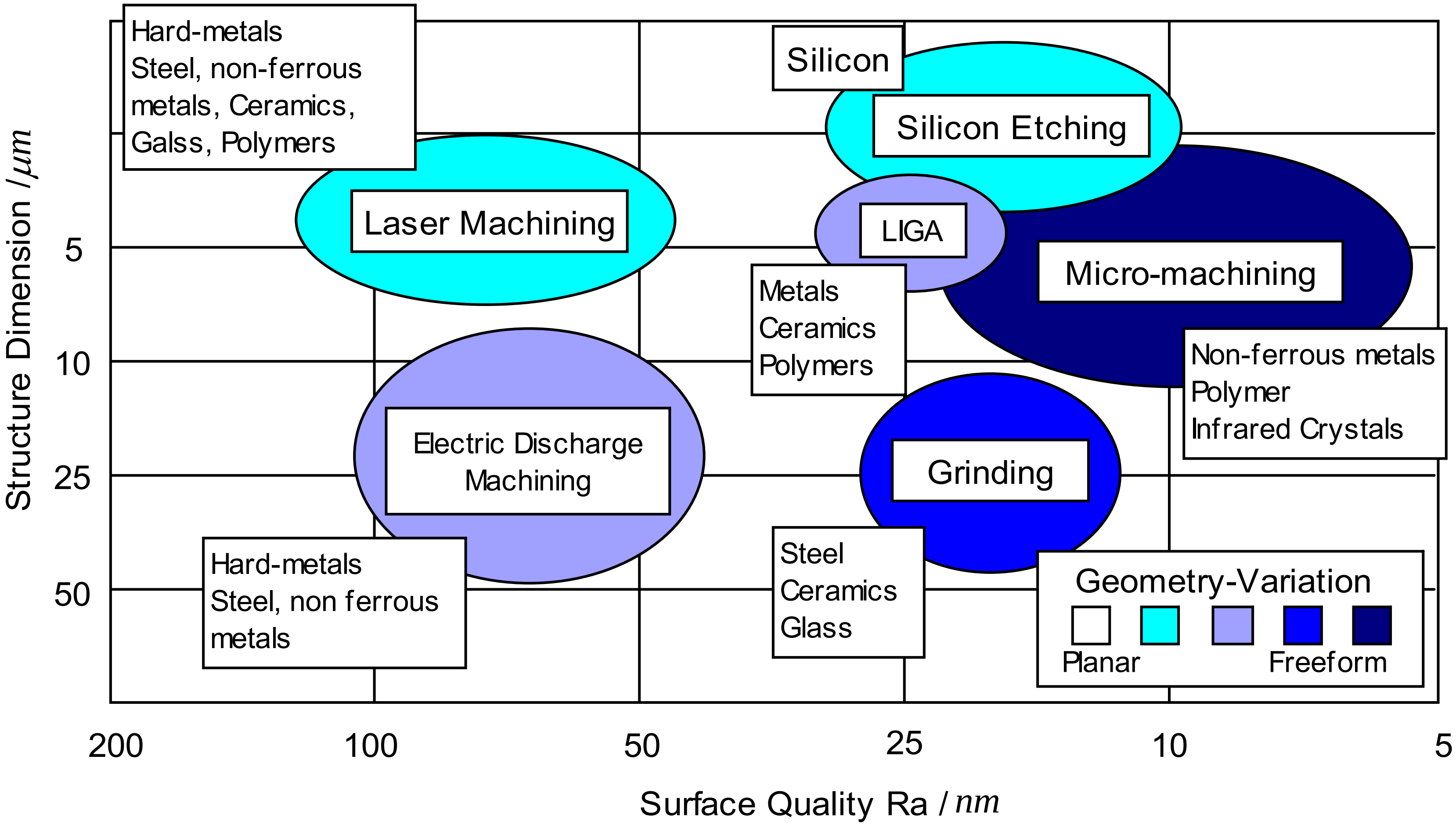
# 2. 微细机械加工技术

- 微细机械加工（Mechanical Micro-Machining）通常指1mm以下微细尺寸零件的切削加工，其加工误差为0.1μm～10μm 。
- 加工单位可以到分子级或原子级。
- 微切削机理: 切削在晶粒间或晶粒内进行，切削力要超过晶体内分子、原子间的结合力，单位面积切削阻力急剧增大。
- 超微细加工：通常指1μm以下超微细尺寸零件的加工，其加工误差为0.01μm～0.1μm。
- 精度表示方法：一般尺寸加工，其精度用误差尺寸与加工尺寸比值表示；微细加工，其精度用误差尺寸绝对值表示。

# 微切削加工特点


Research methods in micro cutting mechanics
Experimental studies
(Micro milling, SPDT, Fly cutting, etc.)
Modelling & simulation studies
Analytical modelling
Mechanistic modelling
Numerical simulation (FEM, Molecular dynamics)
Conventional cutting process mechanics
Micro cutting processes
Micro turning
Micro milling
Micro drilling
Micro grinding
Micro cutting mechanic aspects
Cutting force & energy
Chip & burrs formation
Surface generation
Cutting temperature
Tool wear mechanism
Enabling technologies
Machine tools
Micro tooling
Size effects
Cutting edge radius
Grain size
Material properties
Process variables
V
Tool
R
Challenges and scientific approaches to tackle micro-machinability
High aspects ratio features
Difficult-to-machine materials
Short tool life
200 µm
Vibration assisted micro cutting
Laser assisted micro cutting

# 微切削加工与其他加工方法

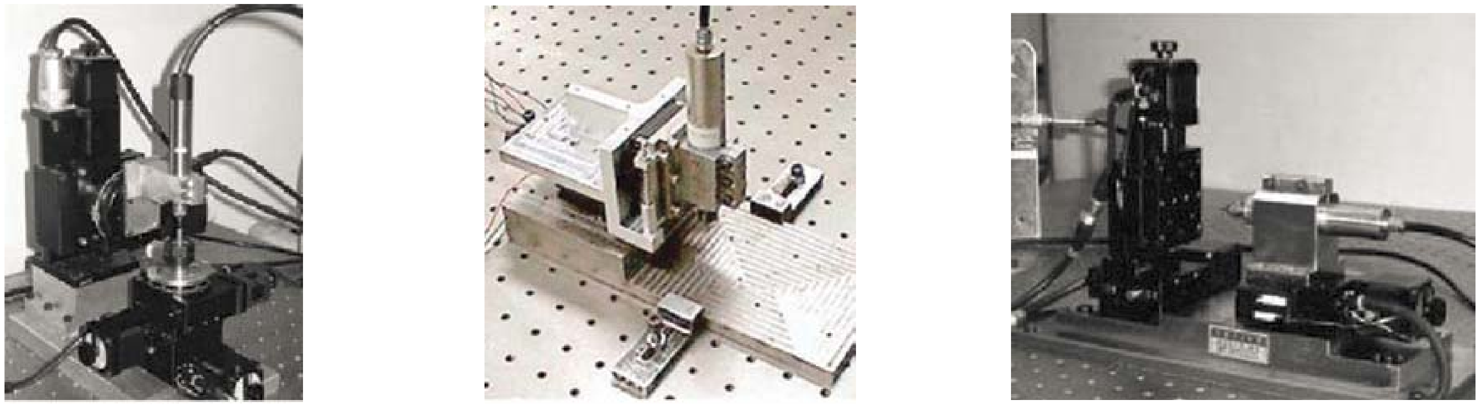


# 微细机械加工设备

- 微小位移机构 ，微量移动应可小至几十个纳米
- 高灵敏的伺服进给系统。要求低摩擦的传动系统和导轨支承系统，以及高跟踪精度的伺服系统
- 高的定位精度和重复定位精度，高平稳性的进给运动
- 低热变形结构设计
- 刀具的稳固夹持和高的安装精度
- 高的主轴转速及动平衡
- 稳固的床身构件并隔绝外界的振动干扰
- 具有刀具破损检测的监控系统。

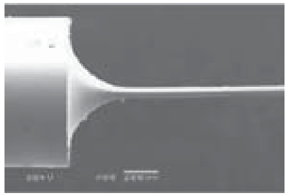
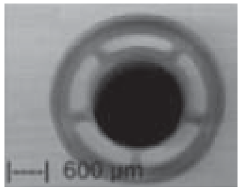
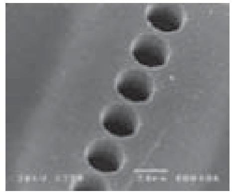
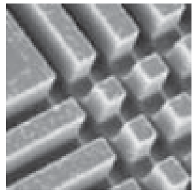
# 微细切削加工机床


(a) Kern micro (b)Fanuc ROBOnano. (c) Moore Nanotech 350FG.



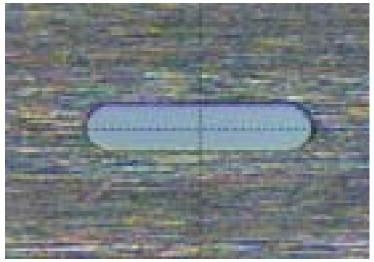
Micro-Machines developed at UIUC, Northwestern, and Brunel University

# 典型微切削加工的几何特点

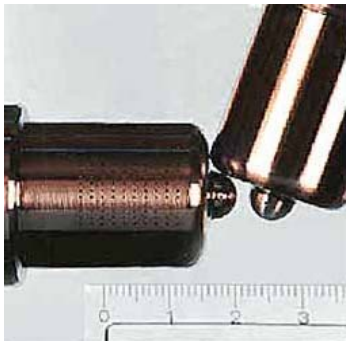
| | Micro turning | Micro milling | Micro drilling | Micro grinding |
|---|---|---|---|---|
| Workpiece Shape | Rotational convex shape with large aspect ratio, such as micro shafts, micro pins, etc. | 3D shape both convex and concave with high aspect ratios and high geometric complexity | Round holes through or blind | Hard and brittle materials; 3D convex and concave shape using micro grinding tips |
| |  |  |  |  |
| Typical size | Down to ϕ5 μm, though 100 μm above more applicable | 50 μm slots are practical applicable | ϕ50 μm holes are practical applicable | Micro structures down to 20 μm |
| Achievable surface roughness | 0.1 μm Ra | Optical surface (<10 nm Ra) via diamond milling for non-ferrous materials | 0.1 μm Ra | advantageous for brittle materials with optical surface finish (<10 nm Ra) |

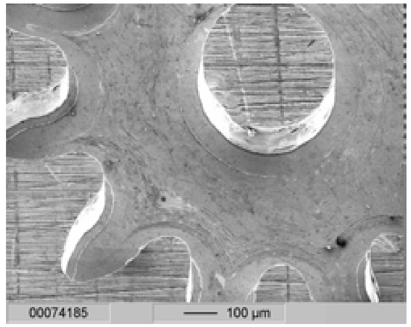
# 应用

100 micro



70 micro



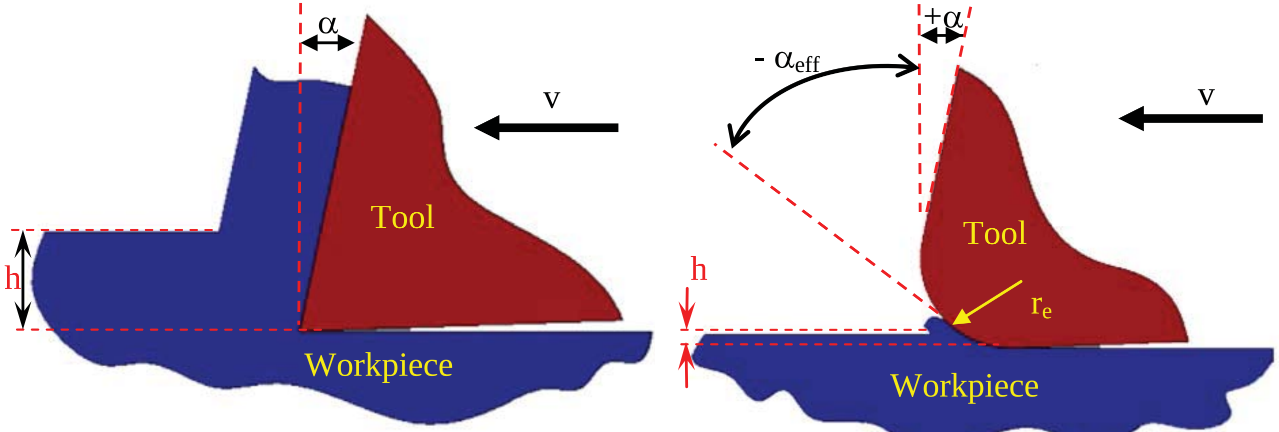



航空航天，精密医疗器械

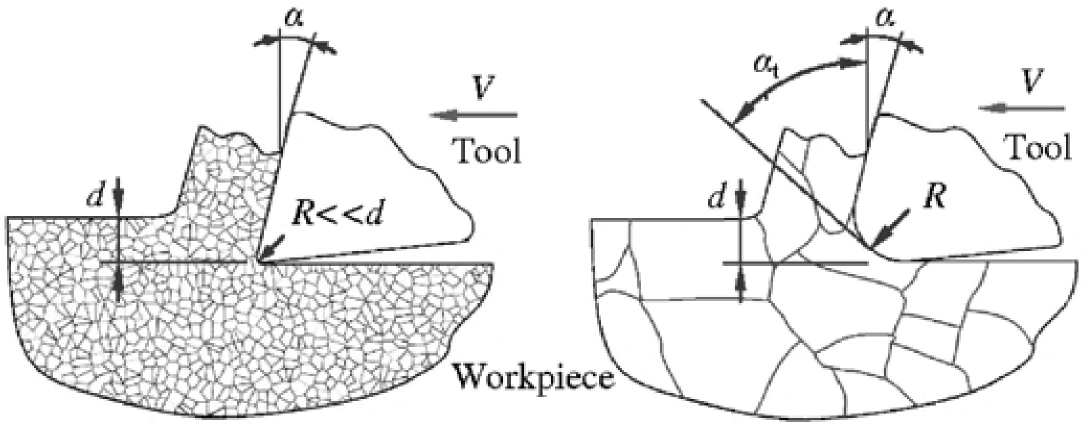
# 3. 微切削与宏观加工机理的主要区别

- Microstructure effect
  - Homogeneous and isotropic, anisotropic machining
- Minimum chip thickness and specific cutting energy
- Surface roughness
- Burr
- Force modeling
  - Empirical, Mechanical, Analytical Models
- tool wear
- sensing and monitoring methods

# 尺寸效应

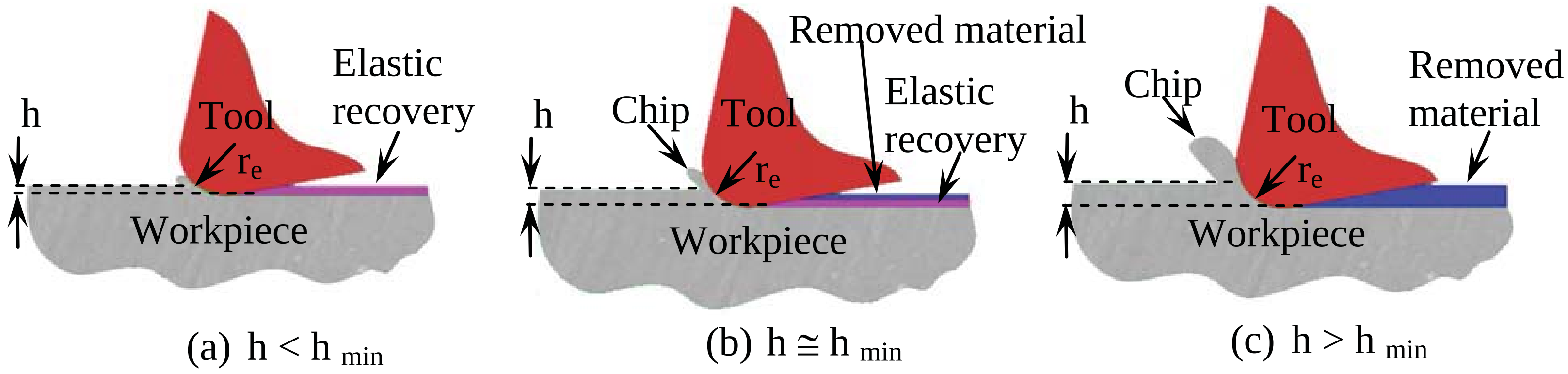



(a) Macrocutting (b) Microcutting



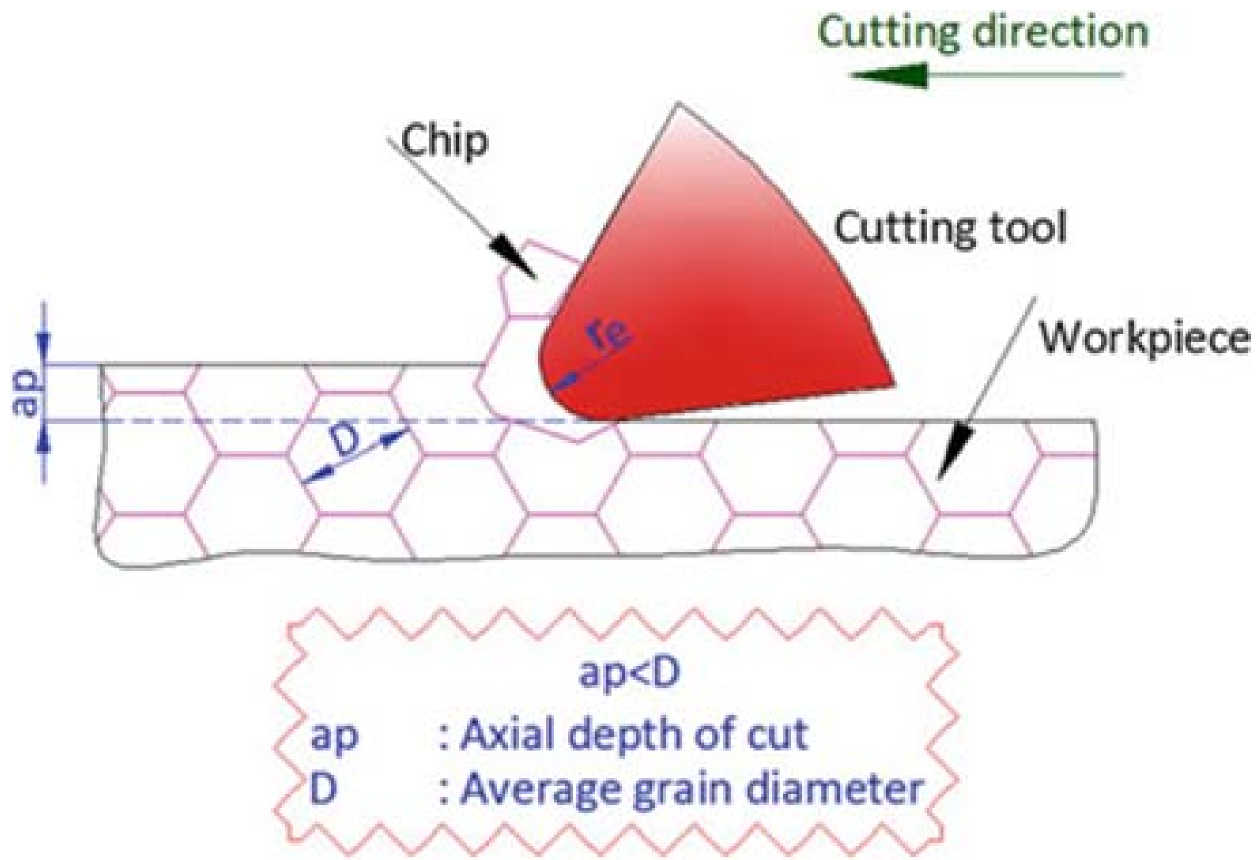

Conventional Cutting Micro Cutting

# 最小切削厚度



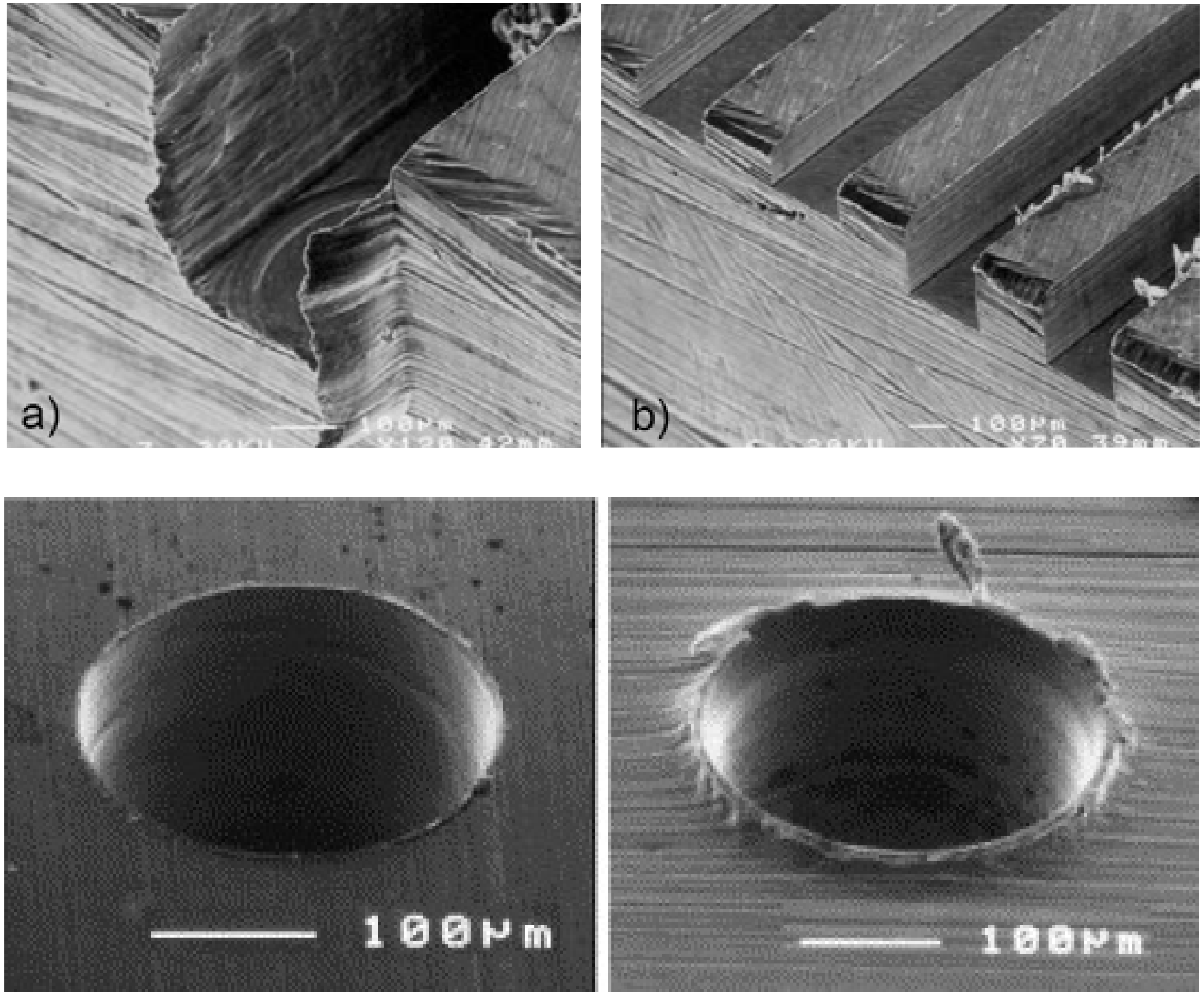

Chip formation relative to minimum
chip thickness in microscale machining

# 各向异性




Anisotropic machining: Brings high frequency vibration, tool wear, surface roughness

# 毛刺

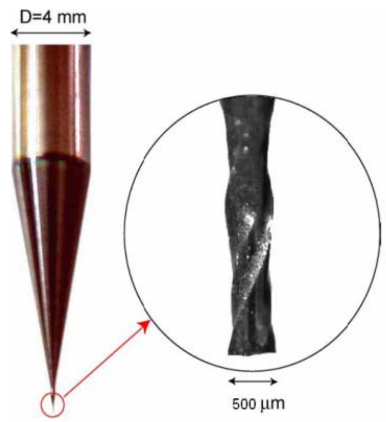


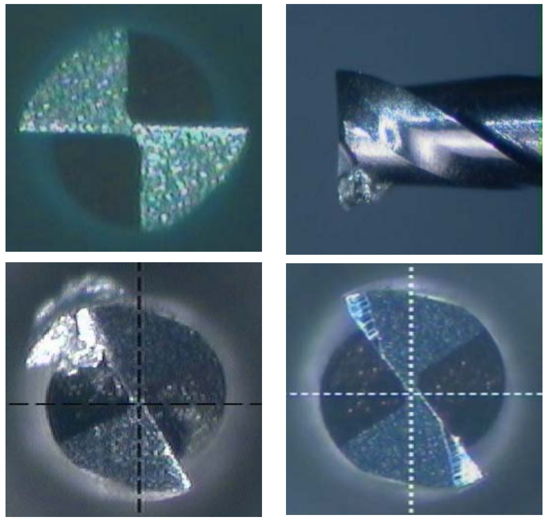
# 4. 研究实例: 刀具磨损与监测

1) 微切削动力学，系统稳定性，过程控制

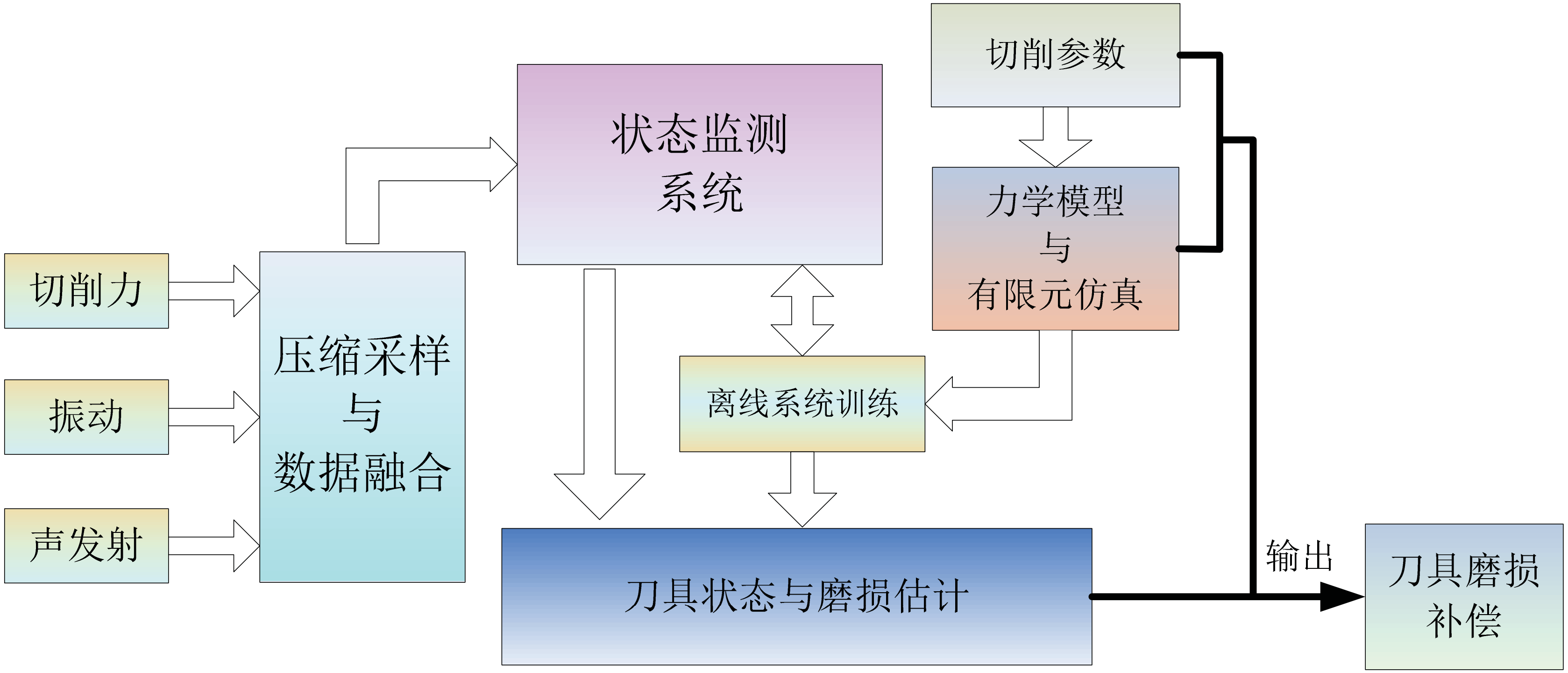
2) 刀具磨损、断裂

3) 加工过程建模与监测



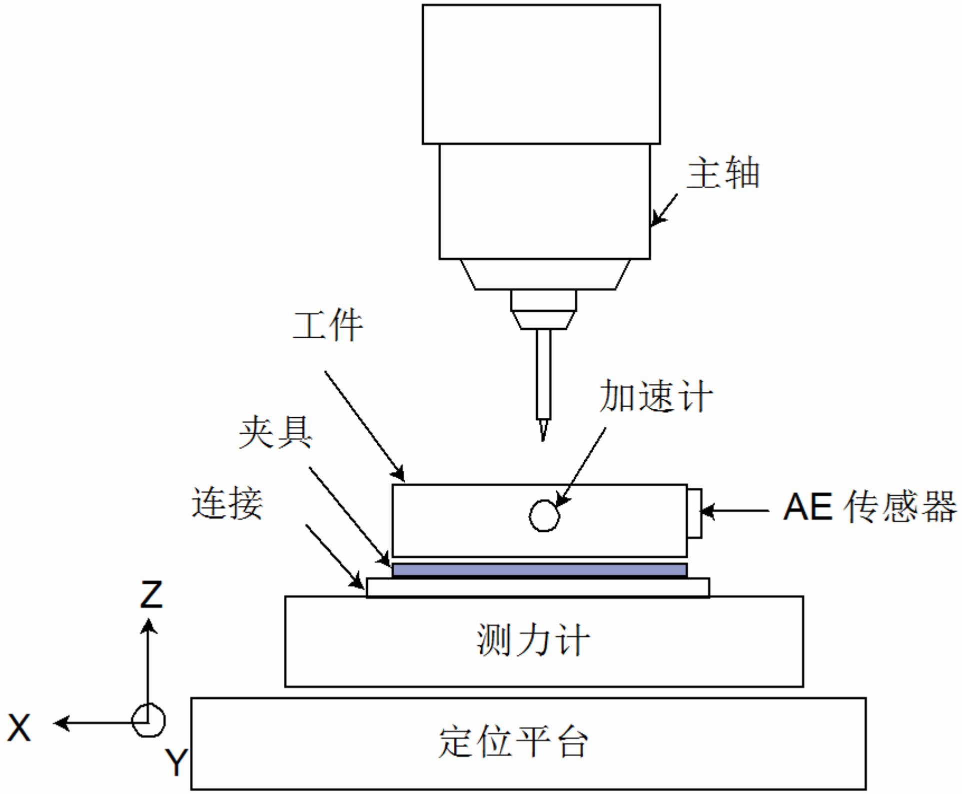



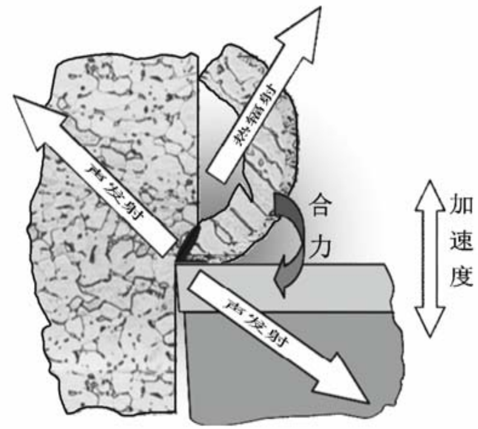
# 4.1 系统方案

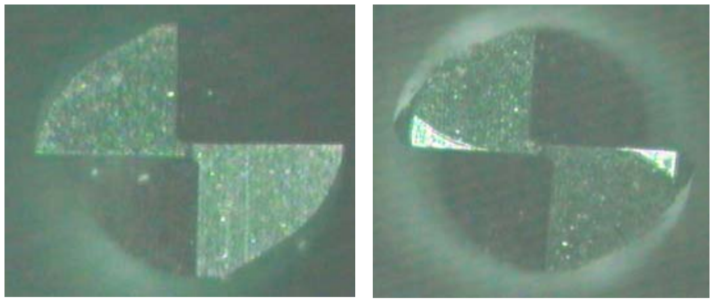


切削参数
状态监测
系统
力学模型
与
有限元仿真
切削力
振动
声发射
压缩采样
与
数据融合
离线系统训练
刀具状态与磨损估计
输出
刀具磨损
补偿

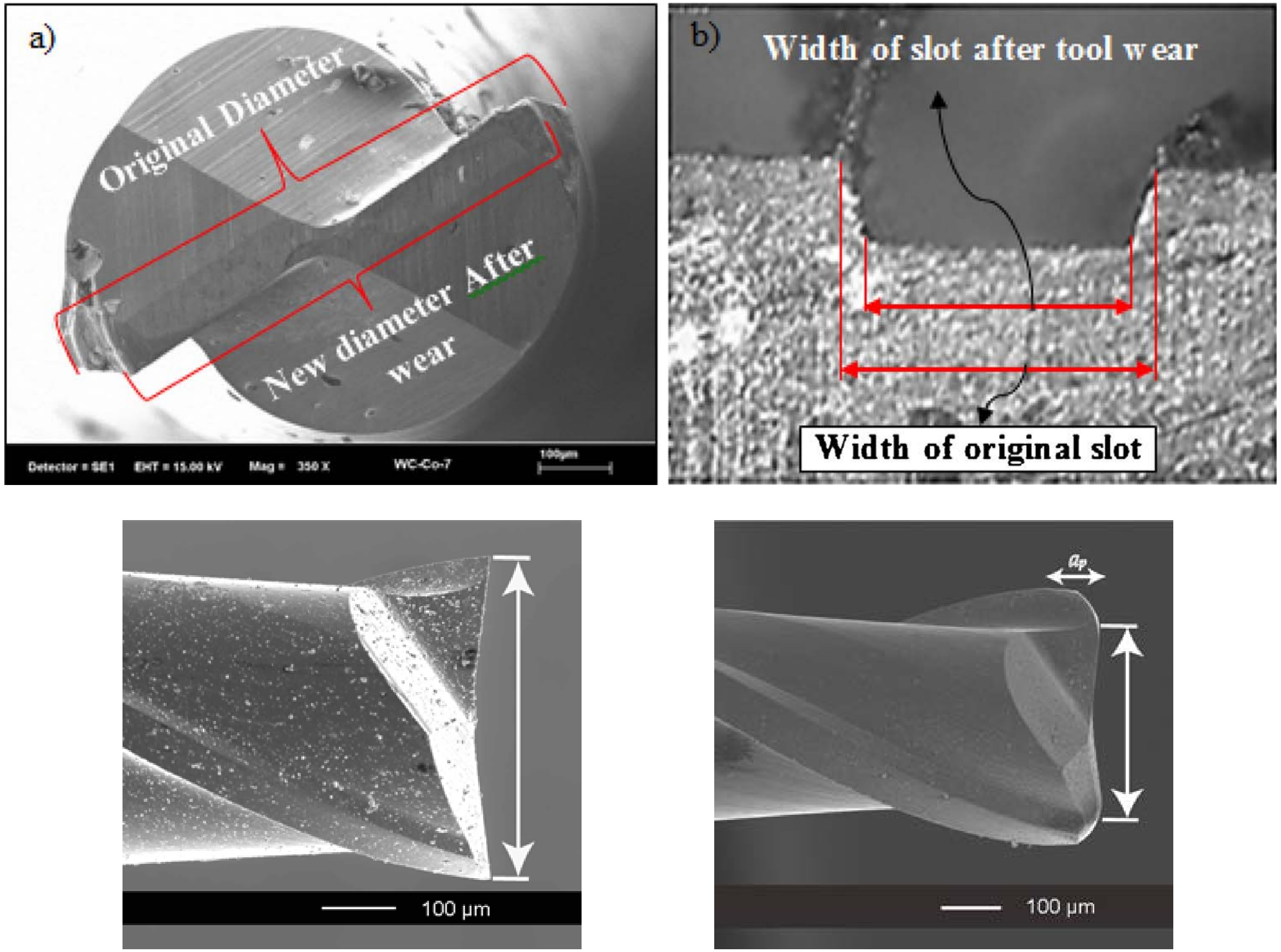
# 实验



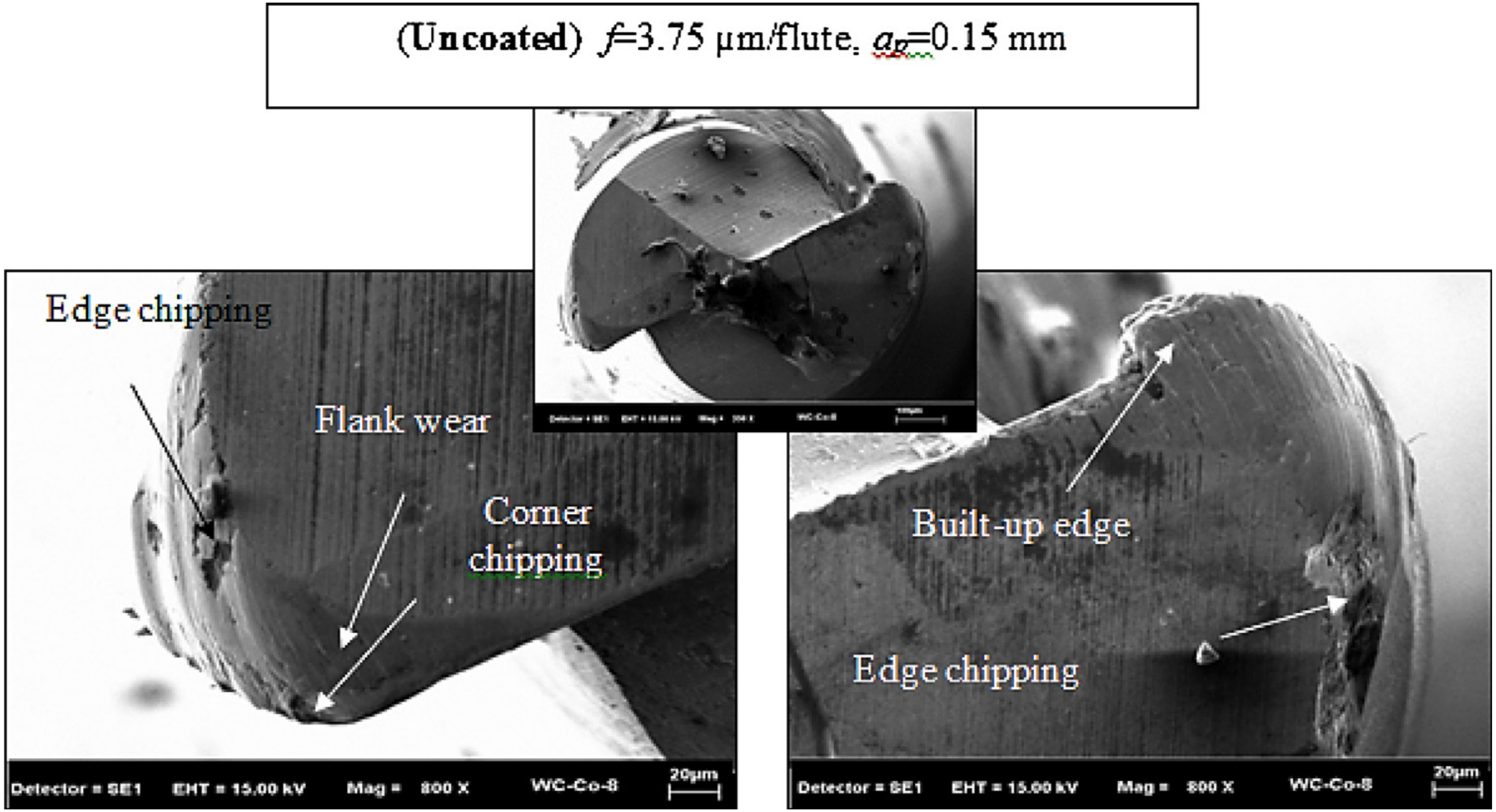



# 4.2刀具磨损与直径尺寸变化



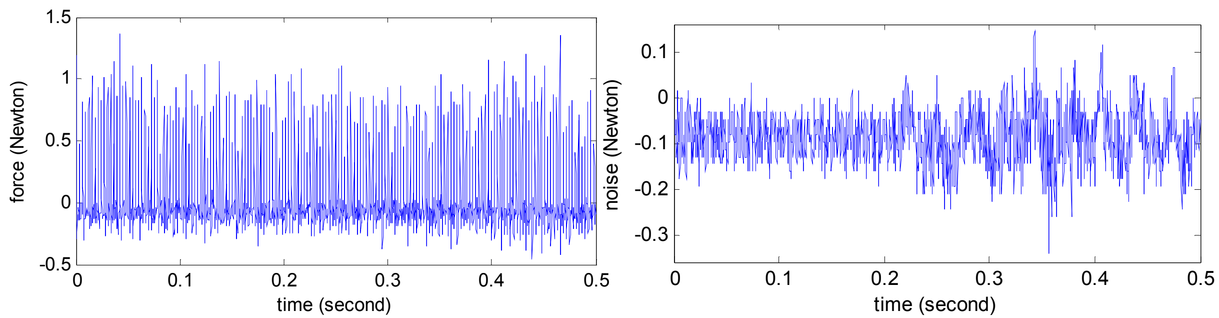

Variations of tool diameter and lot geometry, to determine the tool wear 20

# 4.2刀具磨损电镜扫描图

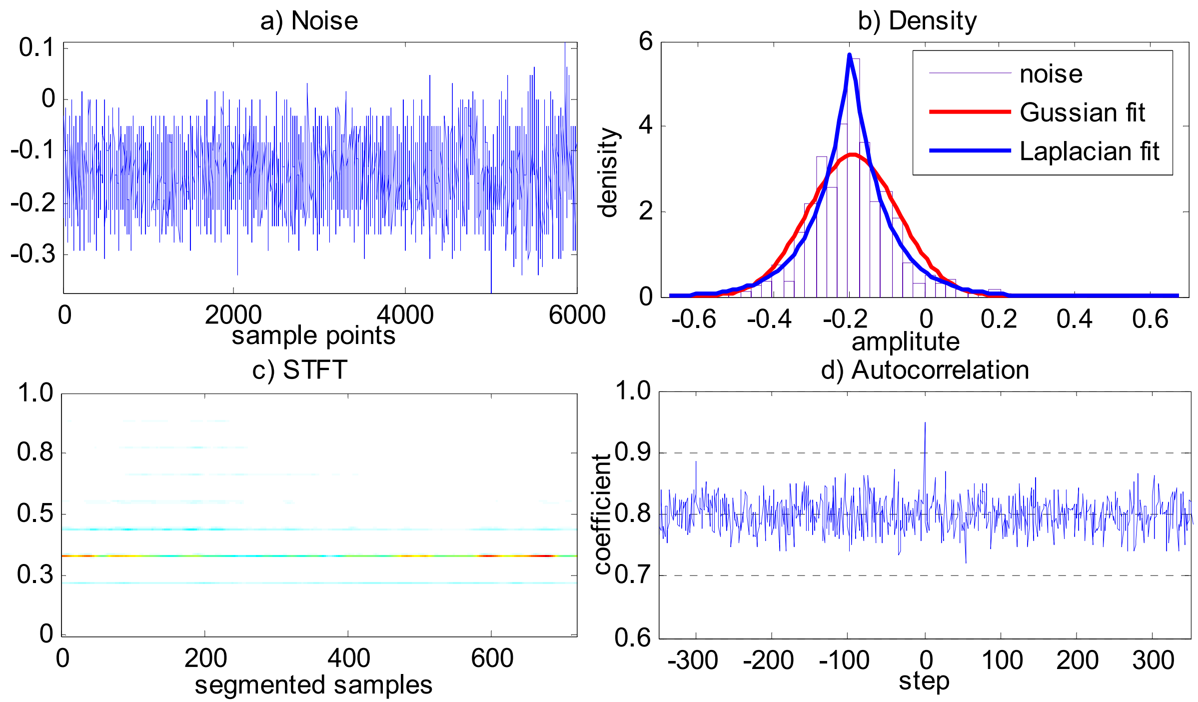



SEM images for uncoated tool after cutting process of 120 mm.

# 4.3 信号监测及处理




SNR low




Non-Gaussian noise

# 4.4 去噪声及刀具磨损状态估计

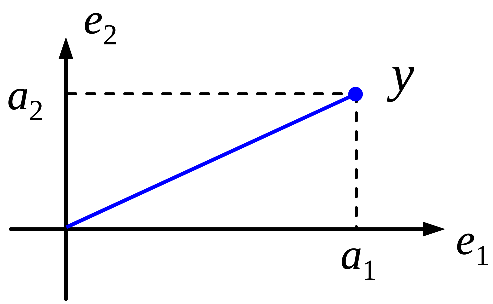
## Sparse representation theory（稀疏分解方法）

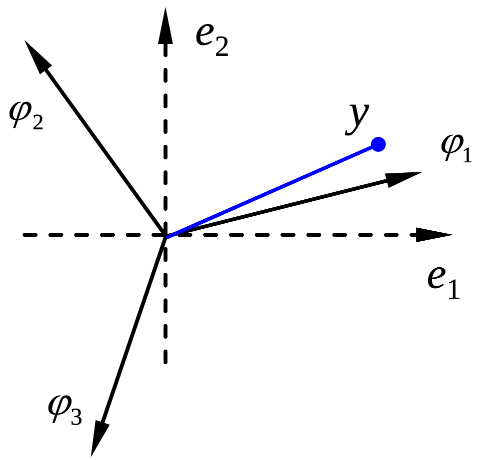
**Motivation:** Large dictionaries incorporate more patterns and increase sparsity. Better for compression, denoising, and pattern recognition.

**Approach:** Represent a signal sparsely in terms of linear combination of atoms in an overcomplete (redundant) dictionary.

$$\min_{x} \|x\|_0 \quad \text{s.t.} \quad \mathrm{y}=\Phi x,$$

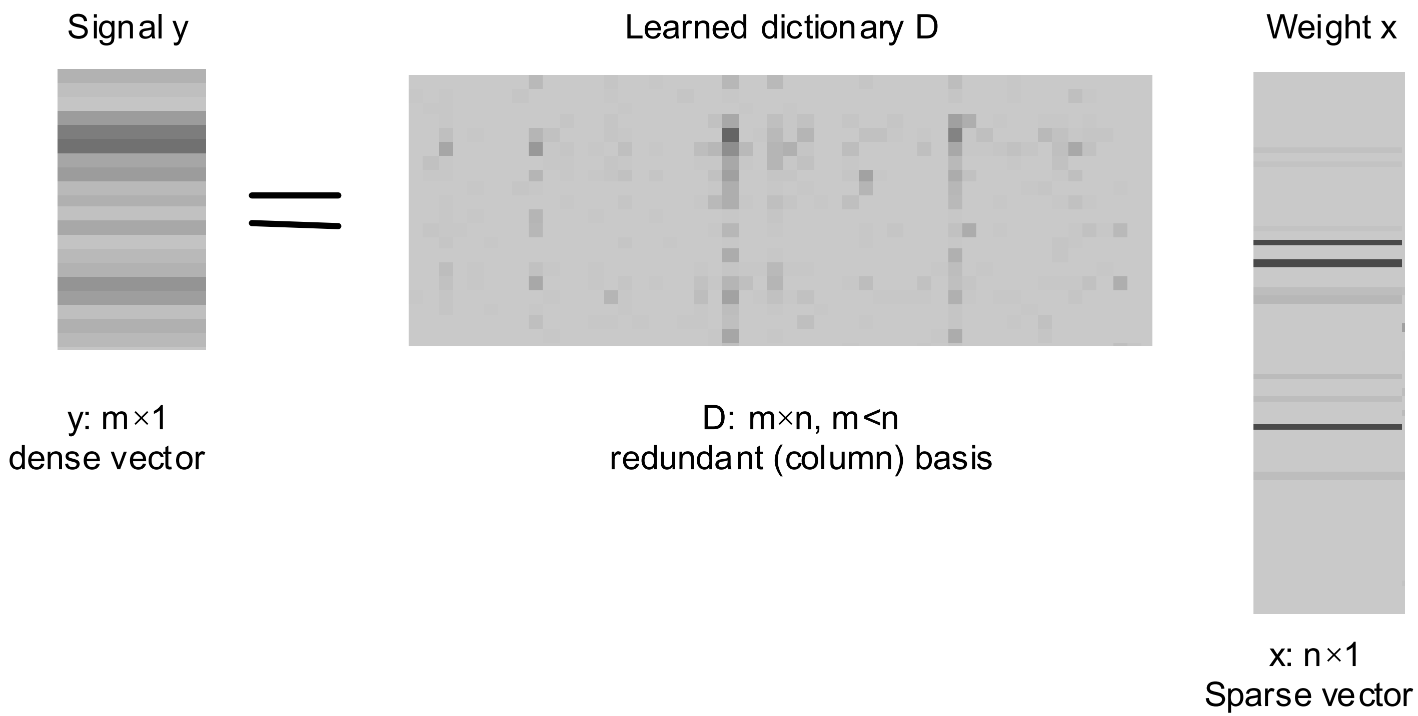
$$\min_{\alpha} \|\mathrm{y}\text{-}\Phi x\|_2^2 + \lambda \|x\|_1 \quad ,$$



# 稀疏分解理论 (续)

## Sparse representation in redundant dictionaries




Redundancy offers a wide choice of atoms to represent the signal.
A smallest linear combination of atoms could be selected to approximate the signal.

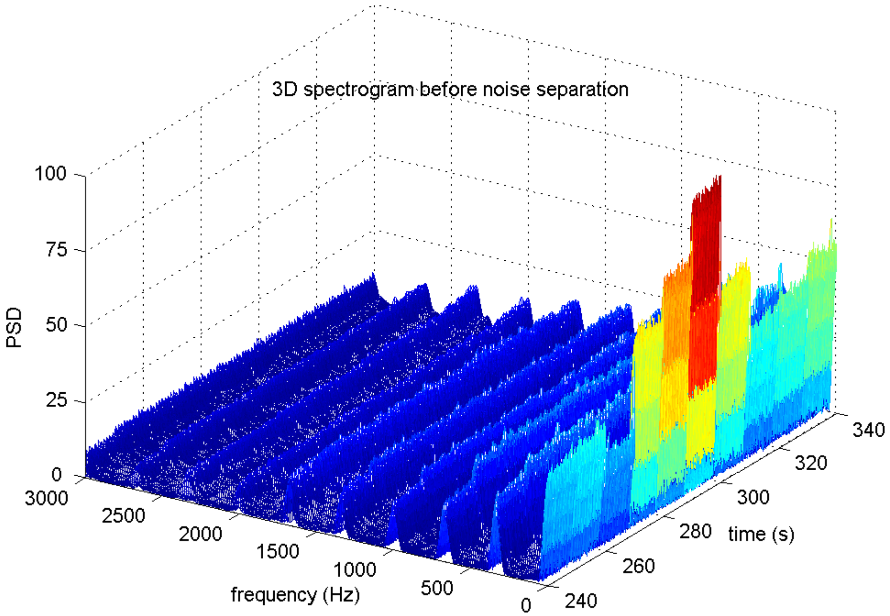
# 构造凸优化问题

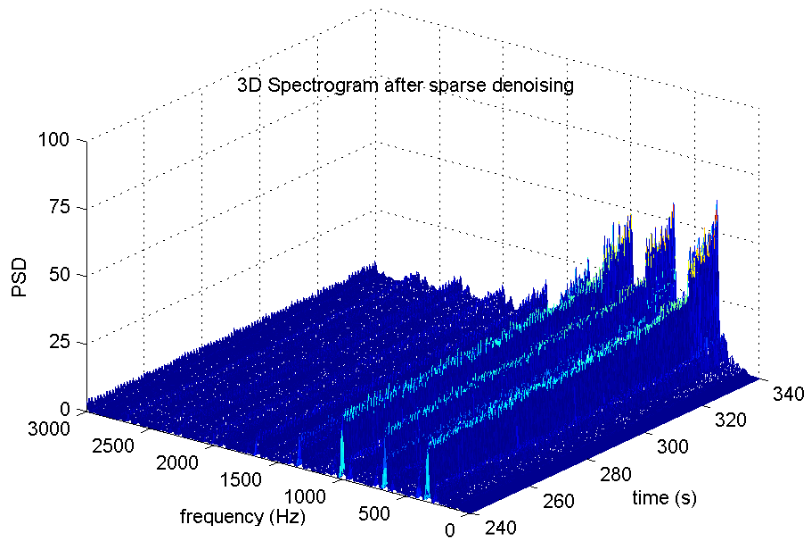
- Dictionary learning process, and optimize objective function *J*,

$$
\begin{aligned}
J &= \max(\text{Discrimination}) + \min(\text{Reconstruction}) + \max(\text{Sparsity}) \\
&= \max(J_1) + \min(J_2) + \max(J_3)
\end{aligned}
$$

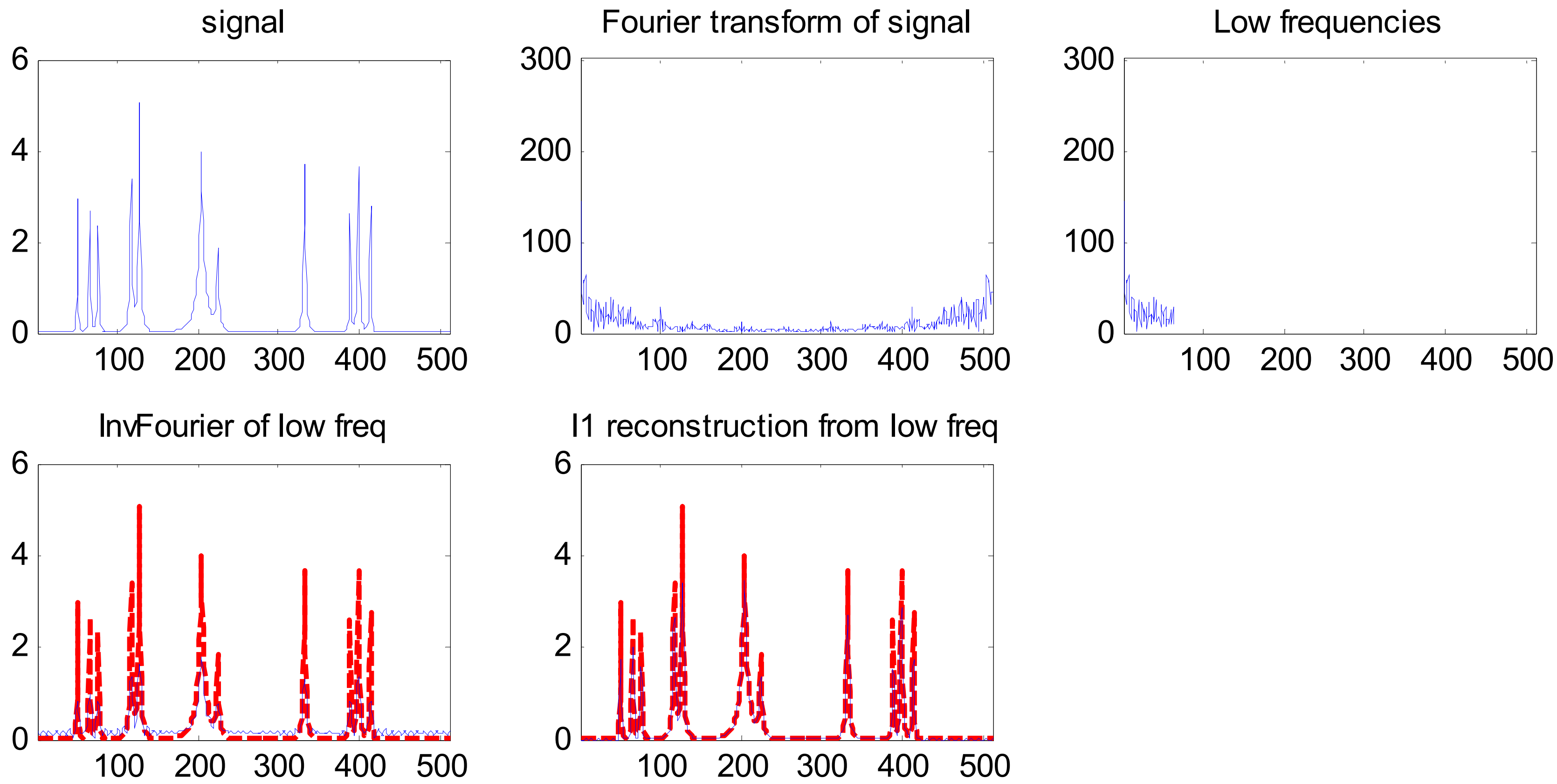
$$
\min \frac{1}{2}\frac{S_W}{S_B} + \frac{1}{2}\lambda_1 \left\| y_i - \varphi_i^{\ T} x_i \right\|_2^2 + \lambda_2 \left| x_i \right|_1
$$

# 4.5 刀具状态监测


3D spectrogram before noise separation
PSD
100
75
50
25
0
3000
2500
2000
1500
1000
500
0
frequency (Hz)
240
260
280
300
320
340
time (s)


3D Spectrogram after sparse denoising
PSD
100
75
50
25
0
3000
2500
2000
1500
1000
500
0
frequency (Hz)
240
260
280
300
320
340
time (s)

# 4.6 压缩采样




实现远低于采样频率信号获取及在线监测

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# 谢 谢！

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