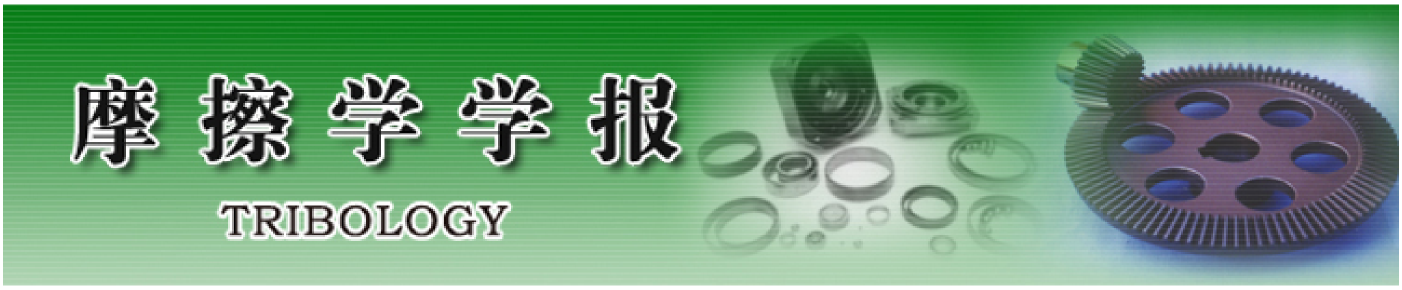

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机械磨损的磨粒检测技术进展

陈　通, 汪久根[*]
(浙江大学 机械工程学院, 浙江 杭州 310058)

摘　要: 机器零部件的磨损是机器失效故障的主要原因，由磨损引发机械故障带来巨大经济损失，有必要开展机械设备的磨损检测. 磨粒检测技术通过磨粒的形状与图像分析，可以认知磨损的机理与磨损过程，实现视情维修，并且实现对机械零部件剩余寿命的预测. 本文中拟从磨粒的检测原理与方法、统计分析、几何分析、图像分割、图像识别与处理、在线铁谱技术与磨粒智能分析，对机械磨损的磨粒检测技术进展进行评述. 铁谱仪的原理有直读式铁谱仪、分析式铁谱仪、旋转式铁谱仪和在线铁谱仪. 基于磨粒的检测原理有铁谱技术、基于霍尔效应的磨粒检测、激光网检测、微流控检测技术、径向磁感应的磨粒检测、静电检测磨粒的方法、超声波反射检测磨粒的方法和并行共振激励检测等. 本文中介绍了铁谱技术的统计分析、几何形态分析、分形分析、图像分割研究、基于图像的铁谱分析、在线铁谱分析和铁谱的人工智能分析进展；另一方面，提出了机械磨损的磨粒检测技术存在的问题与挑战，提出了今后需要研究的问题. 基于机器视觉，自动分析磨粒的大小、边缘形状和表面纹理，得到磨粒的特征参数，用群理论分析磨粒的统计参数，减少对试验分析人员经验的依赖，实现更快、更准确的磨粒特征分析. 基于分形几何理论表征磨粒的几何形态，得到磨粒的尺度不变量. 逆分形分析技术是从小尺度到大尺度，可以对磨粒的几何形态提供新的表征信息. 采用三维磨粒的全信息检测技术，可以提取磨粒的三维几何特征. 针对磨粒几何形态的分形计算，引入粗糙集理论，来提高磨粒图像分割的精度与速度. 新的磨粒产生速率是衡量磨损变化趋势的有效参数，可以预测机械零件的剩余寿命. 两种或者多种检测原理的融合与集成，可以提高监测磨损的准确性，为机器的磨损故障预测提供更高的可信性. 此外，集成不同研究者各自开发的磨粒智能检测分析方法，研制机器磨损故障监测的软件包，实现基于磨粒信息的机械磨损的故障诊断与机械零件剩余磨损寿命的预测.

关键词: 机械磨损; 检测原理; 形态分析; 图像分析; 智能分析
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Progress of Measurement of Mechanical Wear With Wear Debris

CHEN Tong, WANG Jiugen[*]
(*Faculty of Mechanical Engineering, Zhejiang University, Hangzhou 310058, China*)

Abstract: The wear of mechanical parts and elements is the main reason of the failures of machines, and causes enormous economic loss as results of failures of mechanical wear. Thus, the operation conditions of equipment are monitored with respect to wear process and wear state. The wear mechanisms and the wear stages can be studied with the detection techniques in terms of wear debris, and the maintenance based on machine condition and the prediction of the remain service life of mechanical elements and parts can be achieved. The principles of wear debris detection, statistical analysis, morphological analysis, image segmentation and recognition and intelligent examine based on artificial intelligence were reviewed. The ferrography methods have direct reading ferrography, analytical ferrography,

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*Corresponding author. 11825080@zju.edu.cn, Tel: +86-13819105744.

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rotary ferrography and on-line ferrography. The principles of debris detection are classified as ferrography, Hall-effect, laser net fins, microfluidic detection, radial inductive sensor, electrostatic sensor, ultrasonic echo detection and detection method with parallel resonance structure. The state and the art of measurements using wear debris of above different principles were comparatively reviewed. On the other hand, the challenges and existed problems, which need studied further, of wear debris for detection of mechanical wear are proposed and presented. The automatic analysis of debris size, edge profile and surface texture based on machine vision would obtain its feature parameters. The statistical computation with group theory can avoid the dependence on experience of researchers, and achieve more efficient and accuracy analysis of debris features. The characterization of debris morphology with fractal theory can obtain their scale-invariant parameters, and the inverse fractal analysis from small scale to larger scale can provide new information for the debris morphology. The morphological feature extraction based on three dimensional view images for wear debris analysis can present full description of the wear debris. The introduction of the rough set theory to the fractal analysis debris morphology can improve the efficiency and accuracy of the segmentation of wear debris. The birth rate of new wear debris is an effective parameter to assess the wear stage and its tendency, with which remain service lives of mechanical elements can be predicted. The integration of different principal methods can improve the accuracy of wear monitoring, and provide more reliable prediction results for the wear failure of machines. Moreover, an exited problem and useful topic is the integration of the intelligent analysis methods presented by different researchers, and develop one software for the monitoring of wear failure of machines, which is a trend of monitoring method of mechanical wear. The final goals are the automatic failure diagnosis of mechanical wear based on the information of wear debris, and the prediction of remain service life of mechanical elements as results of mechanical wear.

Key words: mechanical wear; detection principles; morphological analysis; image analysis; intelligent examine

磨损是相互接触的物体在相对运动中表层材料不断转移的过程，磨损加剧会导致零件失效，最终引发机械故障. 国外统计资料表明：约有80%的机器零部件是因为磨损失效，50%以上的机械装备恶性事故起因于润滑失效和过度磨损. 美、英和德等工业国家每年因摩擦和磨损造成的损失约占其国民生产总值的2%~7%，零件表面的磨损需要大量的更换配件，这浪费了大量的材料与能源，并加剧了环境污染. 因此，机械磨损的监测是非常重要的技术手段，以期实现对机械零部件的视情维修和对零件剩余寿命的预估.

1 工程意义

机械工程中的各种切削机床，其刀具的磨损影响工件的加工精度，并且消耗更多的电能. 船舶的齿轮箱中的齿轮磨损严重影响推进系统的噪声，齿轮轮齿的疲劳折断还影响机电系统的安全性，回转轴系中滑动轴承的黏着磨损失效会引发严重的事故，推进系统中螺旋桨的严重气蚀磨损，不仅导致噪声升高，而且危害船舶的安全行驶.

高铁的轮轨系统磨损、弓网磨损和齿轮磨损等严重地影响行驶的安全性，轮轨系统的黏滑可能导致列车的脱轨，引发严重的交通事故，另一方面，过高的摩擦噪声也影响乘客的乘车体验. 飞机起落架的关节轴承磨损影响飞机着陆的安全性，航空发动机中的滚动轴承承受的载荷高、转速高且工作温度高，其滚动轴承的疲劳磨损、黏着磨损与安全工作寿命决定了飞机安全飞行的距离.

汽车的驱动系统、传动系统与行驶系统等存在多个摩擦副的磨损，例如，活塞环与缸套的磨损、曲轴轴承的磨损、进出气阀的磨损、变速器与差速器中齿轮的磨损以及轮胎与路面的接触和磨损等. 电动汽车中的电机轴承常常发生电蚀与点蚀耦合的失效，影响电机的使用寿命.

工程机械的磨损问题也很突出，例如、挖掘机斗齿的磨损影响工作效率，盾构机的截齿磨损影响掘进速度与能源利用效率. 其中液压系统的活塞与活塞缸的磨损导致液压油泄漏，密封件的磨损也会引发液压油的过大泄漏以及流体工作压力的降低. 此外，在其他运动副中也存在机械磨损现象，决定了机电系统的正常使用寿命[1-2]，在本文中，称运动副为摩擦副，面接触的低副以及点或线接触的高副，由于高副的接触应力高，更易发生各种机械磨损.

为了减少由磨损引发机械故障带来巨大经济损失，有必要开展机械设备磨损检测工作. Seifert和Westcott等[3-4]在1972年提出了分析磨屑的铁谱技术，机器的零件表面磨损越严重，产生的磨粒就越多，同时磨粒的大小、形状和化学成分也发生变化，他们检测了喷气发动机的球轴承磨损. 铁谱技术可以检测几微米到

20纳米的微颗粒，在润滑油中的微颗粒数目一般可达$1\times10^{12}/\mathrm{cm}^3$. 铁谱技术对于0.1~50 μm尺寸范围的磨粒能够有效地检测，比磁塞法更加灵敏，而且可以对磨粒的种类、数量和分布以及特征参数进行定量分析. 从1980年以后，国内的铁谱分析技术也得到了很好的发展[5-7].

现有多种机械磨损的检测技术，彭鹏等[8]综述了多种磨损检测技术的原理、特点、应用以及存在的问题，介绍了应用较广的放射性检测技术、铁谱分析技术、振动检测技术、声发射检测技术、称重法、测长法、压痕法、电学检测方法和光学检测方法等. 针对需要进行信号处理的振动检测技术和声发射检测技术，阐述了磨损信号特征提取方法以及磨损故障智能诊断技术. 这些检测方法有各自的应用领域，尚未形成1套通用的磨损检测技术，因此，在不同的检测场合需要选择最合适的检测技术. 王少萍与石新发等[9-10]很好地综述了磨粒检测与润滑磨损检测，提出以磨粒数目增加速度来表征摩擦副的磨损状态，磨粒检测与润滑油的劣化程度检测相结合，为机械设备的视情维修与剩余寿命预测提供了有效的技术手段.

目前，磨粒分析技术分析已经成功用于柴油机[9-17]、燃气透平机[18-22]、齿轮传动[23-26]、农业机械[27-28]、高速铁路设备[29]、流体机械[30-32]、RV减速器、滚动轴承和滑动轴承等的磨损的检测和磨损状态的监测[33-36]，另一方面，铁谱技术可以用于高分子材料的密封件磨损监测[37-39]. 磨粒分析技术不仅成功用于多种机械设备的故障诊断，帮助人们认识摩擦副的磨损机理，而且对机械设备的视情维修与零件的剩余寿命预测也提供了技术手段[40-52].

本文中拟从磨粒的检测原理与方法、统计分析、几何分析、图像分割、图像识别与处理、在线铁谱技术和磨粒智能分析对机械磨损的磨粒检测技术进行综述，并提出相应技术的挑战与近期展望，为磨损监测技术的进一步发展提供基础.

2　磨粒检测原理与方法

早期，采用磁塞来收集油液中的磨粒并判断机器摩擦副的磨损程度，后来发明了自动报警技术，当磁塞上的磨粒达到一定厚度，导电的金属磨粒接通电路，从而触发光电报警，提示人们需要更换润滑油或者更换磨损件，如图1所示[1]. 磁塞法对于尺寸大于100 μm的磨粒能够有效地收集与检测，但是对于小磨粒的检测不够灵敏.

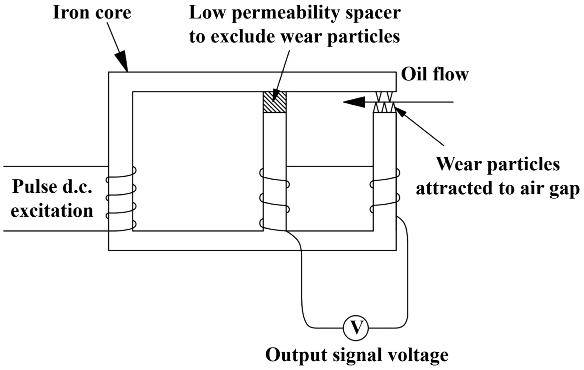


Fig. 1　Detection of wear debris[1]

图 1　磨粒检测[1]

光谱分析润滑油技术能够对尺度小于2 μm的磨屑有效检测，并能对磨屑成份进行定量分析，另一方面，光谱分析不能反映磨屑的形态，也不能将磨屑按其尺寸的大小来排列. 放射性同位素测量方法也能分析磨损过程，但其测试材料的制备过程复杂，一般仅限于实验室中使用，在工程现场不便使用.

由于大多数机械零件用钢铁材料制造，因此，可以采用磁性测量技术来收集或者分析磨粒，分析磨粒的大小分布、磨粒形状和磨粒颜色等信息以诊断机械零件表面的磨损程度. 磁性检测原理的发展催生了铁谱技术的出现，铁谱仪的制作载玻片的过程如图2所示[3]. 首先，收集机器中润滑油的磨粒，然后分析润滑油中的磨粒[3-4]，用溶剂稀释润滑油油样，通过泵将油样抽取流过载玻片，在载玻片下设有磁场强度变化的磁铁，在油样流过载玻片的过程中，大的磨粒首先沉积在载玻片上，然后，小的磨粒也沉积在玻璃片上，如图3所示[3]. 最后，用显微镜来观察和分析载玻片上的磨粒，从而分析机器的磨损机理与零件的磨损程度. 磁性吸附力可以用下式计算：

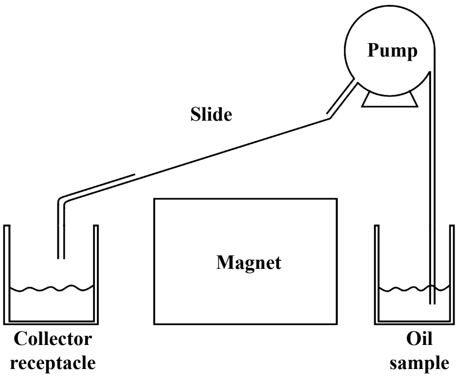


Fig. 2　Preparation of Ferrograph[3]

图 2　铁谱制片[3]

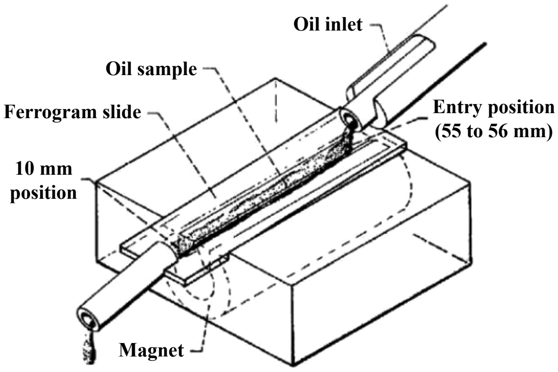


Fig. 3 Principal of ferrography[3]

图 3 铁谱仪原理[3]

$$F_x = M\frac{\partial H}{\partial x} = \sigma_s W\frac{\partial H}{\partial x} \tag{1}$$

式中，F_x为x方向的力，单位为kg·m/s^2；M为粒子的磁力矩，单位为Wb·m；$\partial H/\partial x$为x方向的磁场梯度，单位为mT/m；σ_s为粒子的饱和力矩，单位为Wb·m/kg；W为粒子的质量，单位为kg.

图4所示为典型的铁谱图像[7]，经图像分析，首先可以分析磨粒的形状，并且认知磨损的机理，有微观切削磨损、疲劳磨损、黏着磨损和氧化磨损等；其次按一定间隔时间取得油样，用铁谱分析可以认知磨损的发展过程，铁谱图像分析可以了解零件的磨损程度；最后分析大磨粒与小磨粒的数目之比，可以对机器失效进行预警，随着零件磨损的加剧，油样中大磨粒的数目逐渐增多，球形磨粒的出现是滚动接触疲劳的标志[53]. 铁谱技术的检测结果与扫描电镜和X射线对磨粒的分析结果一致，是1种检测磨损的有效方法，而且铁谱技术的成本最低[54]. 疲劳磨损产生球状磨粒，磨粒磨损产生微小螺旋状、回环状和弯曲线状磨粒，黏着磨损产生片状磨粒，氧化磨损产生浅红色磨粒[55-61]，因此，人们由磨粒形状可以认知磨损机理.

图5所示为1种直读式铁谱仪[35]，图6所示为1种分析式铁谱仪[35]，1990年后，旋转式铁谱仪、直读铁谱分析软件和在线铁谱仪也相继出现[62-63]. 1977年，人们尝试加热铁谱片到320 ℃，持续时间90 s，发现低碳钢磨粒呈现为蓝色，铸铁磨粒变成草黄色，铝、铬和钼的磨粒为白色[64-65]，这是1种磨粒成分的定性分析方法，但是对磨粒的化学成分不能定量分析.

除了铁谱检测以外，其他的磨粒检测技术也得到了发展. Chiou等[66]提出了1种基于霍尔效应的在线检测装置，检测电压差可以测得磨粒数量的变化，如图7所示. Filicky等[67]用激光网技术检测磨粒的尺寸分布、产生磨粒的速率和磨粒形状，如图8所示. Myshkin等[68]提出了基于光学的磨粒谱分析仪，Dempsey等[69]将铁谱检测与振动检测相结合，用模糊数学分析了齿轮的磨损过程. 基于知识图谱或专家数据库的检测，可以分析磨粒的大小、形状、边缘细节、长厚比，颜色和纹理等[44-45,70]，基于数据驱动的磨粒检测技术仍在发展之中.

Raadnui等[71]采用网状电容传感器检测润滑油的劣化、油中污染物和磨粒. Murali等[72]用电容库尔特计数方法，如图9所示，通过微流控技术来监测金属磨损. 姚远等[73]提出了1种旋转式铁谱仪，如图10所示，实现了制谱、油样清洗和供应的自动控制. Fernandez-Sanchez等[74]提出了1种融合技术，基于颜色和深度进行检测. 亚克朗大学的Li等[75-79]对磨粒检测技术进行了深入研究，提出了基于磁感应的库特计数法，通过磁感应的变化实时检测磨粒. Li等[78]还提出了并行磁阻-电容振荡方法，实现了对铁磨粒与铜磨粒的检测. 后来，他们将超声波脉冲检测与磁感应脉冲相结合[79]，实现对黑色金属与有色金属的磨粒检测，基于共振频率检测[80]，提出了多路复用的分配式磨粒检测.

Hong等[81]提出了径向磁感应的磨粒检测方法，如图11所示，他们用双激励源结构，改进了磁场分布，此外还建立了相应的数学模型，采用带通滤波与关联算

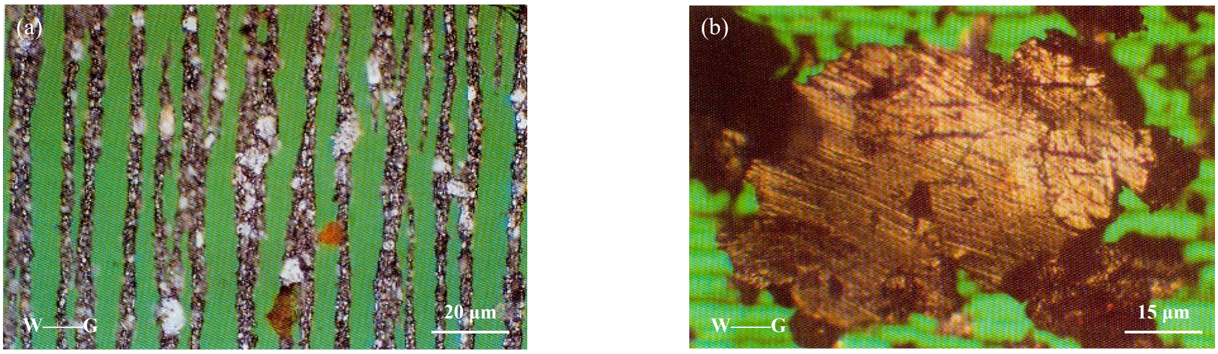


Fig. 4 Typical wear debris of ferrography[7]

图 4 典型磨粒铁谱图像[7]

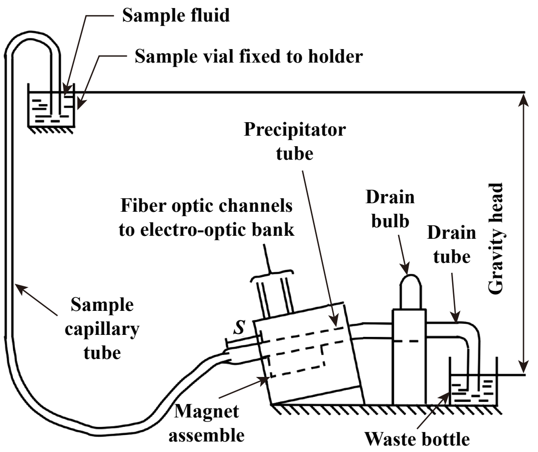


Fig. 5　Direct reading ferrography[35]

图 5　直读式铁谱仪[35]

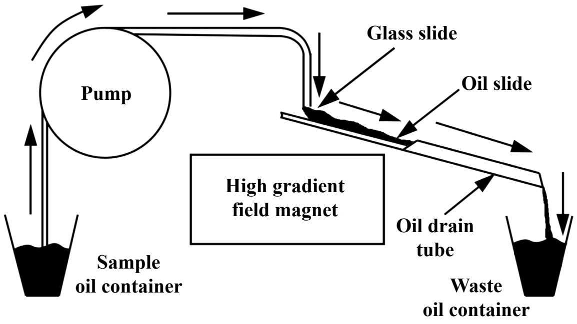


Fig. 6　Analytical ferrography[35]

图 6　一种分析式铁谱仪[35]

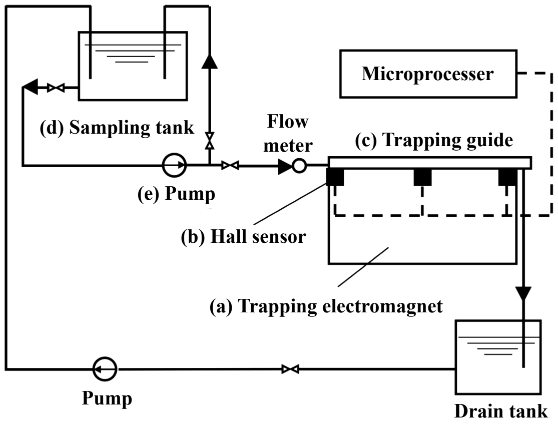


Fig. 7　Detection of debris with Hall-effect[66]

图 7　基于霍尔效应的磨粒检测[66]

法，可以有效检测更小的磨粒[82-83]. 将零件的磨损程度与磨粒数量之间视为正反馈过程，进行了动力学模型分析[84]. Wen等[85]提出了基于静电的磨粒检测方法，如图12所示. Xu等[86]提出基于超声波反射的磨粒检测方法，如图13所示. Peng等[87]提出了1种混合搜索树的辨别方法，可以实现在线磨损监测. Zhu等[88]采用阵列传

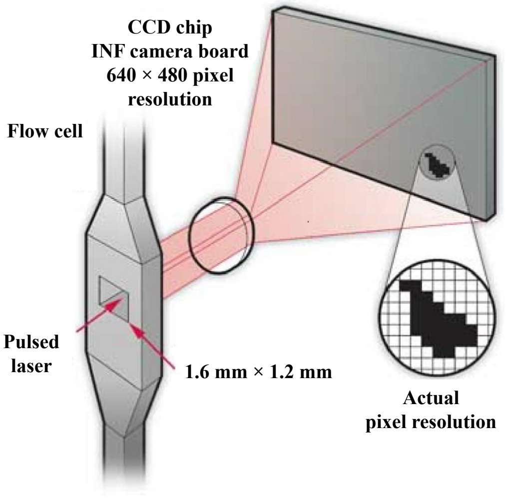


Fig. 8　Detection principle with laser net fins[67]

图 8　激光网检测原理[67]

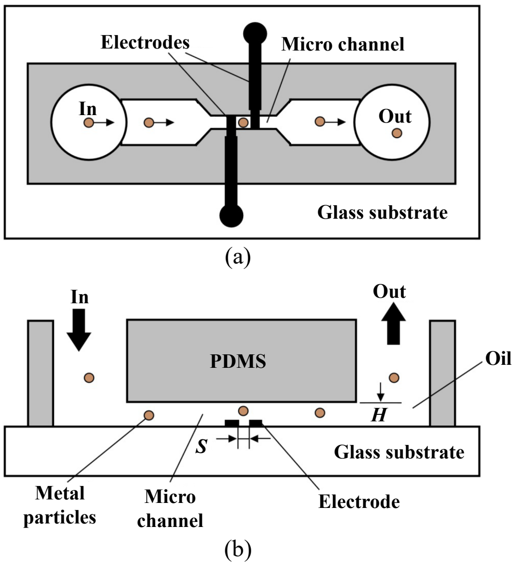


Fig. 9　A microfluidic detection method: (a) top view; (b) front view[72]

图 9　微流控检测技术：(a)俯视图；(b)正视图[72]

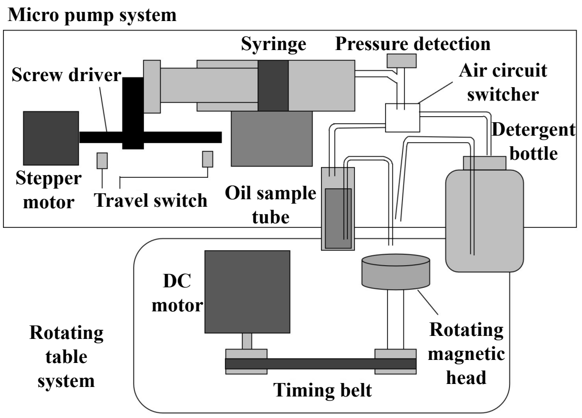


Fig. 10　A rotary ferrograpghy[73]

图 10　旋转式铁谱仪[73]

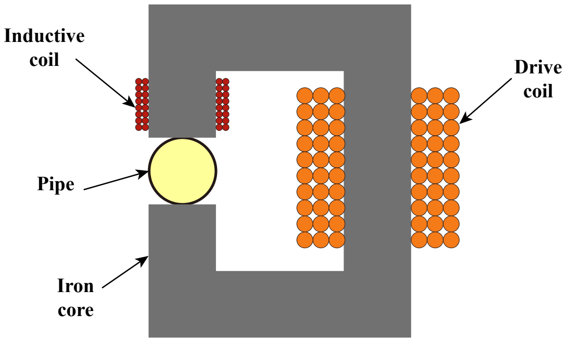


Fig. 11 Debris detection with radial inductive sensor[81]
图 11 径向磁感应的磨粒检测[81]

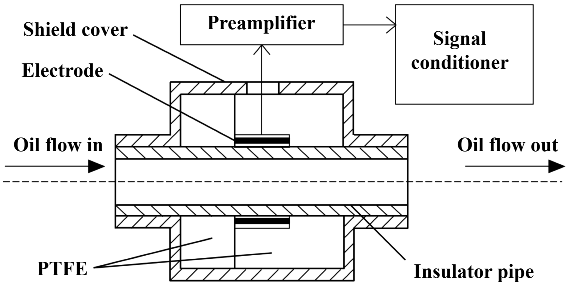


Fig. 12 Electrostatic sensor for debris[85]
图 12 静电检测磨粒的方法[85]

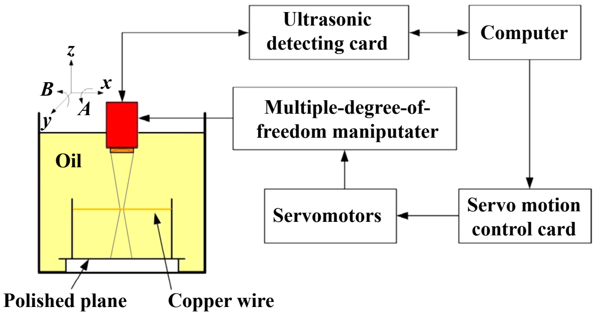


Fig. 13 Ultrasonic echo detection for debris[86]
图 13 超声波反射检测磨粒的方法[86]

感器检测磨粒，检测原理为磁阻-电容-电阻振荡技术，并且提出了同步采样技术. Jia等[89]采用并行共振激励线圈增加阻抗变化，如图14所示，可以提高对小磨粒的检测能力，并且可以实时检测. Xiao等[90]提高了磁场梯度，进行了铁谱检测，他们认为，当油液中磨粒的水平低于250 g/m^{3}时，铁谱检测是1种有效手段；当磨粒水平超过1 000 g/m^{3}时，铁谱检测不能有效检测零件的磨损失效[91].

磨粒检测技术分结果表明，摩擦或者黏着磨损产生的磨粒呈片状，微观切削或者磨粒磨损的磨粒为微小的螺旋状、环状或者弯曲的线状，疲劳磨损的磨粒为微小的球状，氧化磨损的磨粒呈现为红色的颗粒，由磨粒的形状，人们可以推知零件磨损的机理. 磨粒检测分析不仅可以监测机器中零件的磨损程度，而且可以辅助摩擦副的机械设计，与X射线分析、扫描电子显微镜(SEM)、放射性检测、原子吸收和发射谱分析相比，磨粒分析具有更好的经济性和优势.

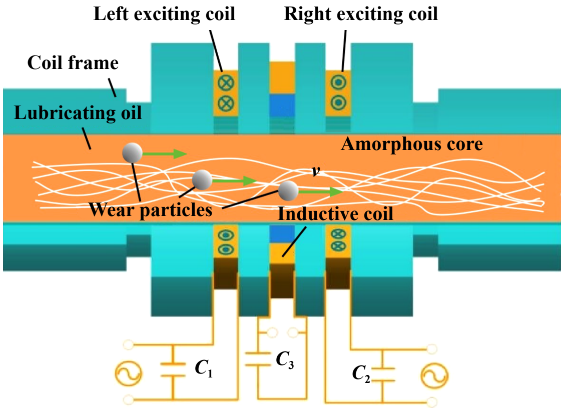


Fig. 14 Detection method with parallel resonance structure[89]
图 14 并行共振激励检测法[89]

3 磨粒检测技术的统计分析

现代机器结构越来越复杂，按时维修机器需要拆开机器检查，降低了机器的生产力，并且耗时和费力,铁谱技术提供了1种视情维修机器的技术手段. 在机器的初期磨损阶段，铁谱中可以发现多种混杂的磨粒，在剧烈磨损开始前，铁谱中发现大量的球状磨粒，这些球状磨粒是零件表面材料的疲劳磨损产生的，另一方面，在剧烈磨损前，油样中小尺寸磨粒的数目急剧增加，小磨粒与大磨粒的数目之比也急剧增大.

铁谱分析可以认知机器磨损机理的转变过程，摩擦副润滑状态的膜厚比、法向载荷、相对运动速度、环境温度和润滑剂的污染情况等都影响磨损过程，并且这些参数的改变导致磨损机理发生变化，即发生磨损机理的转变. 铁谱检测表明，油液中的小磨粒数量较多，而大磨粒数量较少，如图15所示，m为磨粒质量，单位为mg，N为磨粒数量. 铁谱分析可以分析磨粒的数量和大小的分布特性，并且这些参数都具有统计特性[92-96]，Hofman等[11]采用磨损的严重指数I_s来评价磨损状态.

$$I_s = (A_L + A_S)(A_L - A_S) = A_L^2 - A_S^2 \tag{2}$$

式中，A_L为大磨粒的最大面积比；A_S为小磨粒的最大面积比.

用铁谱仪监测磨损程度的参数，记D_L为铁谱片上大磨粒的密度，D_S为铁谱片上小磨粒的密度. 表征磨损程度的参数有[25,27-29,59]：D_L+D_S、D_L−D_S、$D_L{}^2$+$D_S{}^2$、(D_L−

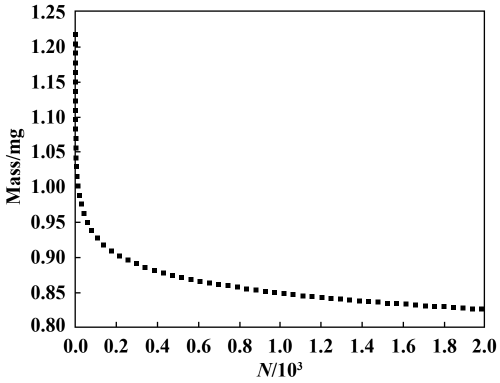


Fig. 15　Number of debris versus its mass

图 15　磨粒的数目与磨粒质量

$D_S)/(D_L+D_S)$、$(D_L-D_S)/D_S$及$D_L(D_L+D_S)$. 1990年, 将专家系统技术与铁谱技术相结合, 黄碧华等[44-45]提出了柴油机磨损状态监测和故障诊断的专家系统.

3.1　磨粒的统计分析

铁谱图片中的磨粒的大小和形状呈现多样性, 具有统计特性, 这也反映了磨损过程的复杂性[97-117]. 早期, 人们对铁谱图像进行统计分析, 以确定剧烈磨损的发生与否, 并分析磨损机理的转化[99]. 1933年, Rosin和Rammer提出磨粒分布函数为

$$P(x)=\exp\left\{-\left(\frac{b}{x-x'}\right)^{n}\right\} \tag{3}$$

式中, $P(x)$是尺寸小于x的磨粒的概率; x'是概率为零的最小磨粒大小; n和b为拟合参数.

1983年, Roylance和Pocock[98]提出的磨粒概率分布为

$$P(x)=1-\exp\left\{-\left(\frac{x-x'}{b}\right)^{n}\right\} \tag{4}$$

则磨粒的平均值为

$$\bar{x}=b\Gamma\left(1+\frac{1}{n}\right)+x' \tag{5}$$

方差为

$$v=b^{2}\left[\Gamma\left(1+\frac{2}{n}\right)-\left\{\Gamma\left(1+\frac{1}{n}\right)\right\}^{2}\right] \tag{6}$$

中位数为

$$N_{\mathrm{m}}=b(\ln 2)^{1/n}+x' \tag{7}$$

机器运行状态用S表示为

$$S=b\left(\frac{n-1}{n}\right)^{1/n}+x' \tag{8}$$

磨粒的平均大小, 即一阶矩为[44]

$$\bar{x}=\sum_{i}x_{i}p(x_{i}) \tag{9}$$

二阶矩为

$$v=\sum_{i}(x_{i}-\bar{x})^{2}p(x_{i}) \tag{10}$$

三阶矩, 即偏态为

$$s=\sum_{i}(x_{i}-\bar{x})^{3}p(x_{i}) \tag{11}$$

四阶矩, 即峰态为

$$k=\sum_{i}(x_{i}-\bar{x})^{4}p(x_{i}) \tag{12}$$

相对偏态为

$$s_{\mathrm{r}}=\frac{s}{v^{3/2}} \tag{13}$$

相对峰态为

$$k_{\mathrm{r}}=\frac{k}{v^{2}} \tag{14}$$

朱新河与严新平等[110]提出用劣化值来判断机器的磨损程度, 他们定义的劣化值K为

$$K=\begin{cases}1, & t\geqslant A\\ \dfrac{t-B}{A-B}, & B<t<A\\ 0, & t\leqslant \mathrm{B}\end{cases} \tag{15}$$

式中, t为某一铁谱定量参数的实测值; B为机械设备处于正常运行阶段的定量参数值; A为某一铁谱定量参数的极限值, 即机械设备达到极限磨损状态的定量参数值. 当$K=0.0$时, 机械设备处于最佳运行状态; 当$0.0<K\leqslant 0.7$时, 劣化轻, 属于正常运行状态; 当$0.7<K<1.0$时, 磨损劣化较重; 当$K=1.0$时, 磨损严重, 已经严重劣化.

统计分析铁谱的磨粒形状, 可以推知磨损的机理, 例如, 金元生等[103-104]针对列车柴油机的磨粒铁谱分析, 认为微小球型磨粒的出现是因为表面的局部闪温高于材料的熔点, 导致接触区内局部材料融化. 微型球磨粒分为光滑表面与粗糙表面2种, 粗糙表面的微球产生于初始跑合阶段, 在跑合结束时, 粗糙表面微球磨粒都消失了, 磨粒的大小随摩擦副的运行时间而变化, 如图16所示[105].

针对磨粒的尺寸、形状与在油中的含量统计分析, 除了铁谱分析方法, 也可以用原子吸收谱分析与扫描电镜方法, 并且后两种方法还可以分析磨粒的化学成分变化. 比较铁谱分析, 光谱分析和磁塞法, 铁谱技术可以作为机器视情维修的重要技术手段[106~110]. 合

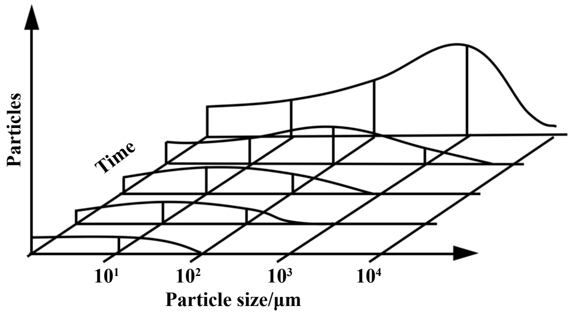


Fig. 16 Variation of particle size with operation time[105]
图 16 磨粒大小的变化[105]

理地安排机器维修间隔时间，既可以避免机器的失效，又可以降低维修成本.

机械磨损具有随机性，因此磨粒也具有统计特征[111-117]，王晓雷等[111]提出用*t*检验的方法来定量分析铁谱磨粒大小，刘岩等[113]提出用随机过程理论分析磨粒的平衡浓度，Cho和Tichy[116]提出用群分析和分类法来研究磨粒的几何形态并且分类磨损的机理. 由此可见，随着研究的定量化分析发展，新的数学工具将被用来分析铁谱信息.

3.2 挑战与展望

(1) 磨粒统计参数的计算耗时费力，目前，基于机器视觉的自动统计分析是磨粒检测技术发展的方向之一，由铁谱仪采集磨粒的大小、边缘形状与边界纹理信息，再由软件系统自动地统计分析磨粒的特征参数.

(2) 新的数学分析方法与磨粒的特征参数分析相结合，也是发展方向之一. 例如，用群理论分析磨粒的统计参数，减少对试验分析人员经验的依赖，实现更快、更准确的磨粒特征分析.

4 磨粒的几何形态分析

基于磨粒的几何形状，可以分析零件表面的磨损的程度与磨损机理，常用的方法有分形几何、傅里叶分析、磨粒半径差分析、表面织构和灰度分析等.

4.1 分形分析

Blau[93]提出分析磨粒的形状和尺寸，从不同的方向分析磨粒的形状，有助于认识磨损机理和分析机器的磨损过程. 自从1977年Mandelbrot[118]提出分形方法以来，分形数学被用来表面粗糙度和表面形貌以及振动信号的分析和特征提取. 1988年，Berthier等[119]首次将分形方法用于磨粒分析，他们用Bouligand-Minkowski方法计算了磨粒的分形维数.

$$d=\lim_{r\to 0}\left(2-\frac{\log A(r)}{\log r}\right) \tag{16}$$

式中，$A(r)$为磨粒面积；r是磨粒的几何表征参数，例如磨粒厚度. 得到的磨粒分形维数为1.06~1.4.

基于润滑剂变化的故障监测首先需要油液取样，收集油液中的磨粒，然后分析磨粒的特征参数. 油液分析的方法有原子吸收发射光谱、X射线荧光法、超声波法、光散射法和铁谱分析法. 磨粒分析的内容有磨粒材料、磨粒尺寸、磨粒形状、磨粒的含量和磨粒大小的分布[105].

随着计算机图像分析技术的进步，分析铁谱的磨粒图像，计算磨粒的表面形貌、边缘形状和边缘形貌，可以监测机器的运行状态和诊断机器故障. 与高阶傅里叶分析比较，分形维数的分析方法能够更好地表征磨粒的边缘特征[120]. Podsiadlo等[121]和葛世荣等[122]也用分形维数来评价磨损过程，认为磨粒分形维数的变化预示着磨损状态的改变. Beddow等[123-124]用傅里叶分析方法分析了磨粒边缘特性，分析了磨粒尺寸、形状和表面纹理. 除了快速傅里叶分析外，还可以用功率谱分析方法来分析磨粒，并与磨损图的绘制联系起来，铁谱技术对磨损的分析结果可以直接指导摩擦副的抗磨损设计[123-126].

西澳大利亚大学的Podsiadlo和Stachowiak[127-132]对磨粒的几何形态进行了深入的研究，他们分析了磨粒磨损与磨粒的分形维数之间的关系，认为用表面形貌仪测量磨粒，但是磨粒太小不便于测量，用原子力显微镜测量磨粒，磨粒尺度太大，也不便于测量. 用激光共聚焦显微镜或者干涉显微镜测量时水平分辨率太低，他们提出用扫描电镜和立体照相技术来分析磨粒的三维特征，用Hurst取向变换来分析磨粒形态，用分割迭代函数系统来揭示磨粒表面形貌信息[127-128]. 后来，他们用这一方法研究了分形不变量，即磨粒形貌的特征参数与磨粒的尺度无关，为磨粒形状和表面形貌的研究提供了有效的计算机数字处理方法[129-132].

袁成清等[133-137]对比分析了码尺法、功率谱法和结构函数法，用割岛法和计数盒法计算了表面和磨粒的分形维数，并且重建了表面形貌[133]. 他们用小波理论和激光共聚焦扫描显微镜分析了零件表面和磨粒，并重建了磨粒的三维形貌[134-135]. 后来，他们还研究了摩擦过程中表面粗糙度的转变过程，认为磨粒的表面几何形态包含有机器状态监测的有用信息[136-137]. 用激光共聚焦扫描显微镜测量可以分析磨粒的三维形貌特征，袁成清等[138]研究了柴油机的跑合过程与稳定磨损过程.

Podsiadlo和Stachowiak[139-141]基于磨粒分类，分析了表面特征参数，例如粗糙度、方向性、同质性和周

期性等，磨粒的纹理参数有面积、外缘、凸性和距角参数，以期实现磨粒的自动分类. 首先，需要建立磨粒形态的分类数据库，然后进行基于三维磨粒形貌的可靠准确的表征，最后建立磨粒分类系统，减少铁谱检测对技术人员经验的依赖，实现自动检测. 文献[142-144]也研究了磨粒的几何形态与磨损机理和磨损程度之间的关系，如果要建立磨粒形态与不同磨损机理之间的关系，仍需要进一步的研究.

4.2　挑战与展望

(1) 基于分形几何理论表征磨粒的几何形态，得到磨粒的尺度不变量，是磨粒分析技术发展的方向之一.

(2) 为了自动地判断磨粒的几何形态并对磨粒加以分类，并且与摩擦副的磨损机理和磨损状态联系起来，首先需要建立具有庞大的磨粒数据库，为更准确地诊断磨损程度提供必要的基础.

(3) 新的分析工具与磨粒检测技术相结合也是今后的发展方向之一. 将人工智能理论与磨粒几何形态和特征参数分析结合，可以减少磨损故障诊断的工作量、缩短磨粒的检测分析时间，并且可以减少对磨粒检测人员专业经验的依赖.

5　磨粒图像分割的研究

磨粒在磨粒图像中会出现重叠，磨粒重叠会影响到磨粒的智能化分析，例如，磨粒重叠使得磨粒数量和磨粒尺寸分布难以得到智能化的统计，从而影响对磨损严重程度的准确评估. 因此，需要研究磨粒图像的自动化分割问题.

5.1　图像分割方法

基于背景色彩识别的磨粒图像分割方法，是通过精度较低的预分割获得图像的背景色彩信息，进而通过识别并剔除背景来提取磨粒，实现了磨粒彩色图像的准确分割. 该方法具有适应性强以及对微小颗粒识别率高的特点[145]. 南京航空航天大学的王静秋等[146-150]深入研究了铁谱图像的分割问题，他们通过分析不同颜色空间下铁谱图像k-means颜色聚类效果，提出在CIELAB颜色空间利用二维颜色分量进行k-means均值聚类的算法，从而实现铁谱图像背景和磨粒的分离. 将k-means颜色聚类结果作为基础图像，利用阈值法分别针对背景和磨粒提取区域极小值，从而获得背景和磨粒标记图像，在此基础上利用标记分水岭算法实现了铁谱图像磨粒沉积链自动分割. 后来，他们又将分水岭算法与群体聚类算法结合，用以分割磨粒图像[148]. 将标记分水岭算法与灰色聚类算法结合，可以准确分割链状的大磨粒和小磨粒[149]. 他们将深度卷积神经网络用于磨粒分割，提高了磨粒分析的速度与精度[150-151].

基于磨粒图像局部颜色纹理，可以对大磨粒的聚集进行分割，而对于小磨粒的聚集，需要放大磨粒图像，然后进行磨粒分割[152]. 针对反射光铁谱图像中的磨粒分割，基于磨粒的边缘检测和等值分类，Feng等[153-154]解决了一些磨粒异常明亮或异常色暗的问题，并且他们解决了油液中微小气泡对在线磨粒检测的影响.

磨粒重叠会导致磨粒数量和磨粒尺寸分布难以被智能化统计，为此，浙江大学的彭鹏等[155-156]提出了1种改进U-Net卷积神经网络的RV减速器磨粒图像分割方法. 首先，考虑到原始U-Net网络不能实现重叠磨粒分离，设计了磨粒边缘分割网络来辅助模型分离重叠磨粒；其次，考虑到磨粒边缘像素数远少于图像背景像素数，提出了2种新的损失函数来解决磨粒边缘分割中的样本不平衡问题；最后，设计了注意力机制模块，从复杂的磨粒图像中提取磨粒特征. 试验结果表明，提出的方法不仅可以实现磨粒和背景的分割，还可以实现重叠磨粒的分离. 相比于传统的分割算法以及深度卷积神经网络分割算法，提出的方法可以获得更好的磨粒图像分割结果，良好的分割结果可为智能化地分析RV减速器的磨粒奠定了基础.

5.2　挑战与展望

(1) 目前，磨粒的自动检测和分类仍是未能成功解决的问题，需要引入新的图像分析方法，例如粗糙集理论，来提高磨粒图像分割的精度与速度.

(2) 将人工智能学习引入磨粒图像的分割，在庞大的磨粒图像库的基础上通过几何分析、边缘检测和颜色分析实现磨粒图像的自动分割是可以期待的.

6　基于图像的磨粒分析

1976年，Odi-Owei等[92]首次将数字图像处理引入铁谱技术[46]，基于磨粒图像分析技术，可以研究磨粒的尺寸分布、单个磨粒的形状和磨粒的边界曲率，为铁谱图像的自动分析提供基础.

6.1　磨粒图像分析

磨粒图像的分析方法有灰度理论、傅里叶分析和激光共聚焦显微镜测量[157-158]. Peng等[159-160]将金属磨粒分为6种，即摩擦、微切削、球状、层状、疲劳块状和严重滑动磨损颗粒，结合灰色系统理论和模糊逻辑方法，分析了磨粒的三维形貌，包括磨粒的边界形貌与表面形貌. 白俄罗斯的Myshkin等[161]用RGB和HSI颜色模型，基于磨粒颜色分析了多种材料的磨粒，其中H

是像素的色调，S是饱和度，I是亮度. 采用阈值分析和二维磨粒图像分析，Cho等[162]提出了磨粒的几何特征参数. 何晓昀等[163-164]的研究表明，HSI模型比RGB色彩模型优越，简化特征参数可以进一步直观分类磨粒，计算图像覆盖面积比率，用线性回归分析机械的磨损变化趋势.

磨粒图像分析方法还有聚类树分析、模糊聚类分析、统计分析、灰色目标理论和灰色关系分析、加权滤波、图像增强、图像腐蚀以及主分量分析等[165-168]. 例如袁伟等[169]提出的径向凹度差分析，此外还有铁谱分析软件系统、深度卷积神经网络[170-171]和多特征的异类信息融合方法等[172]. 目前，计算机的图像分割与图像分析方法也被应用于磨粒的铁谱图像分析[173].

铁谱图像分析技术也可以与其他故障诊断方法相结合，例如振动检测，可以提高磨损故障诊断的准确性[174]. 近年来，人工智能技术与图像分析的结合，也提供了新的磨损故障诊断方法[175].

6.2 挑战与展望

(1) 计算机图像分析是软件工程的重要组成部分，目前已经有多种方法. 将计算机图像分析技术转移用于磨粒图像分析，这是目前发展方向之一. 基于磨粒图像的故障诊断技术，可以应用计算机领域的研究成果，以期实现磨粒图像的自动分析.

(2) 目前已有较多的磨损磨粒图像资料，但是由于机械磨损机理的多原理性、磨损过程转变的复杂性和时变性，目前的磨粒图像的标签学习样本数量仍然很少. 如何提升磨粒图像标签学习数量，仍是基于磨粒分析的智能故障诊断的基础性问题.

7 在线铁谱分析

在线故障监测可以为机械设备的正常运行提供保障，也可以尽早发现设备故障，从而及时维修，降低维修成本. 磨粒的在线分析方法有光学的方法、磁感应方法、阻容的方法和声学的方法. Raadnui[49]对在线铁谱分析进行过很好的综述，在齿轮转动的正常运行阶段，针对故障分析，铁谱分析技术优于振动监测方法[176]. 根据Centers的观点，1979年Bowen[177]首次提出了在线铁谱的检测方法，在线铁谱的检测过程如图17所示.

7.1 在线铁谱分析

在线铁谱技术可以实时监测机械的磨损状态，在复杂大型设备的故障诊断中有重要作用[178-179]. 利用光电传感器和计算机技术，刘岩等[180]研制了1种新的在线铁谱技术，可以对大于5 μm的磨粒实现有效监测. Zhu等[181]提出在线检测方法，如图18所示，可以用磁感应效应来监测铁磁性磨粒，用电涡流效应来检测非铁磁性磨粒.

刘岩和谢友柏等[180,182-187]对在线铁谱技术进行了深入的研究，他们用光纤通信技术研发了在线机器状

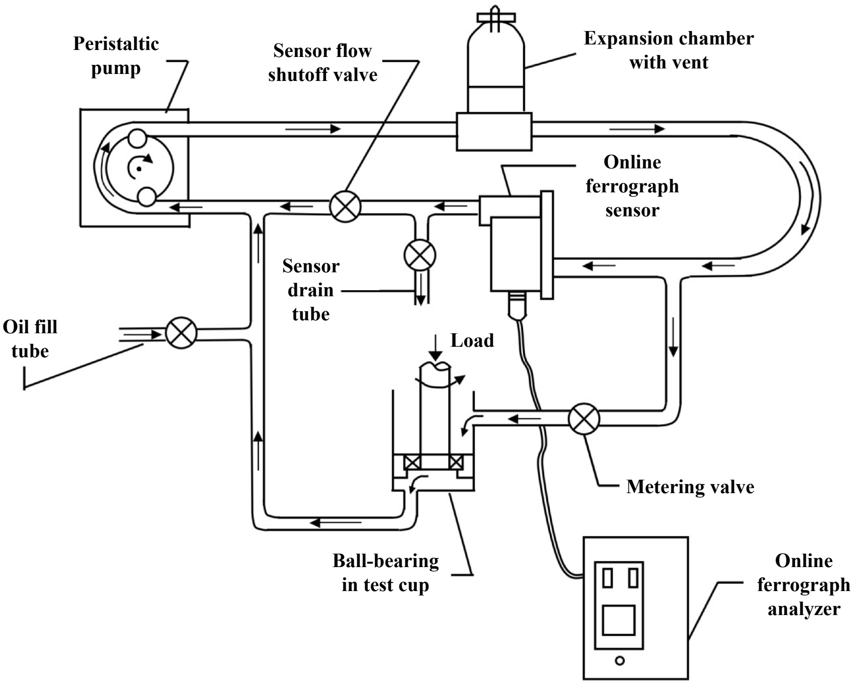
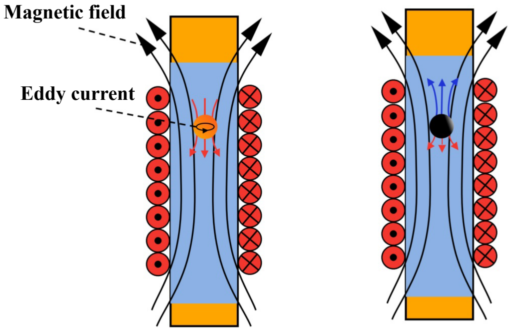


Fig. 17 Online ferrography[177]

图 17 在线铁谱仪[177]



(a) Non-ferrous debris　(b) Ferrous debris

Fig. 18　Online detection of wear debris[181]

图 18　在线磁性颗粒检测[181]

态监测系统，测量轴的振动和位移以监测机器中多点的故障信号. 在单通道铁谱仪的基础上，他们研制了多通道在线铁谱仪，切换通道时，油液的互相污染问题仍有待解决. 基于动态随机过程理论，刘岩等分析了油样中磨粒数目的平衡含量，他们建议，取样油液的量大于100毫升可以提高铁谱技术检测的精度. Hong等[188]采用2个检测器，采用分数微积分的方法来检测磨粒，避免了滤波、降噪和门槛值设定问题，简化了信号处理过程. Fan等[189]采用小波变换方法与峰态分析方法避免了对机器早期故障的漏检与错误报警，提高了在线铁谱检测对故障预警的可信性.

西安交通大学的武通海和谢友柏等[190-203]对在线铁谱技术进行了很多研究，他们用铁谱技术分析了磨损速率与机理，探讨了铁谱图像的数字化处理方法，分析了自动阈值法的应用，计算了磨粒沉积过程. 他们改进了铁谱仪的磁铁布置结构，用反射光、透射光或者这2种光同时照射铁谱片，针对不同污染程度的油样，分析了多种参数的有效性. 他们对磨粒图像进行了HSI (H为色调; S为饱和度; I为强度)颜色分析与灰度分析，提出用磨粒覆盖面积指数的一阶微分和磨粒的当量圆半径来表征磨损速率[195-196]. 用Radon变换分析了在线铁谱的图像，用神经网络技术分析铁谱磨粒图像，实现对机器的视情维修[197]. 针对磨粒图像分割问题，他们提出了分水岭算法和背景去除法[200-201]，通过集成微流控技术和图像采集系统分析了磨粒的三维几何特征[202-203]，这对准确分析磨损机理和磨损状态是有效的.

采用可视化在线铁谱仪，曹蔚和董光能等[204-206]分析了汽油发动机与柴油机活塞环的动态磨损，他们提出了灰度相关矢量机的磨损预测模型. 针对滑动摩擦副，袁伟和董光能等[207]研究了振动对跑合和磨损的影响，他们的试验研究表明，可视化在线铁谱仪是1种有效的磨损监测手段. Feng等[208-209]采用可视化在线铁谱仪分析了四球机和齿轮箱的磨粒变化，他们也用磨粒覆盖面积指数来表征磨损的严重程度. Kuo和Chiou等[66,210]采用电磁铁和光电传感器结合，应用霍尔效应来在线检测磨粒，分析磨损过程，也取得了成功. Miller等[211]用磁感应传感器在线检测了铁磁性与非铁磁性磨粒，成功用于F22战斗机的发动机磨损监测. 在线铁谱检测技术，也在汽车发动机的磨损监测中得到应用[211-212]，Schomann等[213]采用的是LED光学检测磨粒的方法.

在线铁谱的检测原理有电阻抗检测、声学检测、光学检测、压力检测、磁感应检测、电涡流检测、X射线检测、共振频率检测和静电检测[214-218]. 采用磨粒覆盖面积指数或者磨粒含量指数可以实现对磨损的在线表征，而且后者更优[218]. 目前，在线铁谱分析已经得到应用，但是，提高在线磨损监测的准确性和效率仍是有待提高的方面.

7.2　挑战与展望

(1) 新的磨粒产生速率是衡量磨损变化趋势的有效参数，基于这一思路，可以预测机械零件的剩余寿命. 一般来说，1台机器中有多个摩擦副，油液中的磨粒增加是多个摩擦副磨损的总体效果，如何区分每个摩擦副的磨粒增加数仍是有待解决的难题.

(2) 采用三维磨粒的全信息检测技术可以提取磨粒的三维几何特征，对于正确认识磨损机理、磨损变化过程和磨损机理的转化有重要意义. 因此，三维磨粒信息提取方法仍然需要进一步研究，以期集成到磨粒智能分析软件中，实现磨粒的智能分析.

8　磨粒图片的人工智能分析

早在1950年，图灵就提出了电子计算机与人工智能，并分析了其实现的路径. 1986年，Rumelhart等[219]提出了反向传播算法(BP算法)用于人工神经网络的计算，给机器学习带来了希望. 采用BP算法，当神经网络的层数增多时，很容易陷入局部最优或者过拟合. BP算法是监督学习，训练需要有标签的样本集，但实际的数据多是无标签的，在多隐层的学习结构中，学习过程较慢. 在20世纪90年代，还出现了其他的浅层机器学习模型，例如支持向量机方法和最大熵方法. 2006年，Hinton等[220]提出了减少数据维数的方法，实现了逐层初始化的无监督学习. 2015年，他们又总结了深度学习算法[221]，深度学习算法采用很多隐层，并且在神经网络的训练上采用逐层初始化技术. 随着Alpha Go (人工智能下围棋)的出现，2016年被称为人工智能应用的元年. 深度学习方法，可以分为监督学习

习和无监督学习，监督学习的方法有多层感知机和卷积神经网络等，无监督学习方法有深度置信网、自动编码器、去噪自动编码器和稀疏编码器等. 对于人工智能的理解，出现了进化学派、联结学派、符号学派、贝叶斯学派和类推学派.

1个故障诊断系统主要由四部分组成：数据获取、预处理、特征提取以及选择和分类决策. 与机器学习相结合，诊断机械设备的故障是1种新的思路. 目前，智能故障诊断技术正在快速发展，例如，柔性制造系统中刀具的磨损监测是及时更换刀具的必要基础，然而刀具的磨损过程十分复杂，基于振动加速度信号，用神经网络对钻头的磨损进行检测，以实现对钻头剩余寿命的预测. 故障诊断的方法可以分为基于模型的方法、基于信号的方法、基于知识的方法、混合方法和主动方法.

神经网络的故障诊断技术已经用于发动机、滚动轴承、齿轮、电机、泵和透平机等的故障诊断. 吴晓[222]将人工智能方法的反面选择算法用于航空发动机的故障诊断中，训练的免疫系统能够判定出故障的类型以及发生部位. 针对航空发动机中的减速齿轮箱，Shabalinskaya等[223]检测了疲劳磨损的磨粒.

8.1 磨粒的智能分析

针对磨粒的几何特征提取，采用分形维数来表征磨粒的形貌[224]是有效的技术手段. 1997年，Myshkin和顾大强等[225-226]采用BP网络算法分析了磨损产生的磨粒图像. 自从卷积神经网络(CNN)提出以来，已在磨粒图像识别与分析中得到应用[227-228]，Peng等[229-230]将CNN分析与支持向量机分类器联合，分析了在线铁谱图像. Liu等[231]采用多尺度特征提取方法，用CNN技术分析了链状、球形、微切削和氧化磨粒的分割与识别. 浙江大学Peng等[232-233]在抗干扰卷积神经网络模型中设计了特征干扰层，用来干扰模型训练，增强模型的特征学习能力，然后，通过试验分析了模型在RV减速器转速和载荷变化以及噪声干扰下的鲁棒性. 他们提出了1种改进残差卷积神经网络的RV减速器磨粒图像识别方法，首先，考虑到磨粒样本不足，提出了，1种图块重排列的数据增强方法；其次，考虑到磨粒特征提取冗余，提出了1种特征提取损失函数来优化磨粒特征提取结果；再次，考虑到磨粒尺寸变化范围大，提出了1种多尺度特征提取模块. Xie等[234]研究了铁谱磨粒图像的在线智能识别，分析了磨粒的模糊边界和其复杂表面纹理. Wu等[235]将人工智能技术用于磨粒的微观形态分析，并应用于航空发动机的磨损分析. Gonçalves等[236]研究了磨粒的自动分类问题，他们采用了多层感知器分析.

粗糙集理论也已用于磨粒分析，邢敬华等[237]用粗糙集方法识别磨粒，粗糙集方法与分形几何的结合，可以更准确地分类磨粒，认识磨损机理. 徐晓键与严新平等[238]提出用基于证据推理规则的磨粒类型辨识模型，用于船舶柴油机的磨损类型辨识，可以用不确定、不完整信息来辨识磨粒类型. 任松等[239]提出基于模糊支持向量机的方法，用于油液中磨粒的自动识别.

目前，采用计算机的机器学习，提高了辨识磨粒类型的能力，为准确、早期的机器磨损故障诊断，提供了可行的技术路径[240-242]. 基于CNN的磨粒图像分析和在线磨损监测，其准确率已经达到91.8%[232-233,243-244]. 随着机器学习能力的提高，智能化的磨粒分析、磨损机理分析、磨损状态监测和机械零件的剩余磨损寿命的预测是可以实现的.

8.2 挑战与展望

(1) 近年来，人工智能科学与技术得到快速发展，如何将智能学习应用于磨粒分析、磨损监测和机械零件的剩余磨损寿命的预测是一个新的、有效的技术路径.

(2) 采用光学检测方法采集更多的磨粒信息，分析磨粒的三维几何特征与色彩特征，可以更加全面地认知磨粒产生的原因与磨损机理.

(3) 针对磨粒几何形态的分形计算，目前是从大尺度到小尺度计算磨粒的分形维数. 然而，逆分形分析技术是从小尺度到大尺度，可以为磨粒的几何形态提供新的表征信息.

(4) 2种或者多种检测原理的融合与集成，例如，铁谱检测与振动检测的结合，可以提高监测磨损的准确性，为机器的磨损故障预测提供更高的可信性.

(5) 目前，不同研究者各自开发的磨粒智能检测软件比较分散，如何集成优良的智能分析方法研制机器磨损故障监测的软件包也是今后研究方向之一.

9 结论

铁谱检测技术从其出现以来一直是磨损监测的重要手段，其中铁谱检测技术的研究成果最为丰富. 随着新的方法、新的原理和新的工具的应用，出现了基于霍尔效应的磨粒检测、激光网检测、微流控检测技术、径向磁感应的磨粒检测、静电检测磨粒的方法、磨粒的超声波反射检测与并行共振激励检测等.，同时铁谱技术也处于不断发展之中. 基于磨粒分析的统计分析、磨粒的几何形态分析、分形分析以及磨粒图像的分割研究，基于图像的磨粒分析和磨粒的人工

智能分析也在快速的发展之中. 磨粒分析向定量化和智能化方向发展，不断提高磨损监测的准确性和有效性. 一方面，磨粒监测技术和其他监测技术的融合和集成得到快速发展；另一方面，人工智能和磨粒检测技术的结合会在近来得到发展. 今后，随着粗糙集、逆分形分析和智能算法等的发展，基于磨粒分析技术的智能诊断系统可以为机器的磨损监测、机械设备的视情维修和机器中零件的剩余寿命预测等提供必要的基础技术.

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