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涡轮机叶片磨损测量技术试验研究

齐宏伟, 杨嘉栋, 田殿娟, 李伟顺
(哈尔滨·第七〇三研究所, 黑龙江 哈尔滨 150036)

摘 要: 薄层活化法是一种无需拆卸系统动态定量检测指定零部件磨损的方法。该方法具有灵敏度高、可在线检测和放射性低等特点。本文介绍了薄层活化法的原理和相关技术内容, 并将该技术应用于涡轮机叶片的磨损离线和在线测量, 实现了离线监测三种涡轮机叶片和在线两种涡轮机叶片指定部位的汽蚀磨损状况, 给出了试验的详细过程, 经 53 h 试验, 被测叶片的实测磨损量与称重法获得的结果一致, 测量平均值标准误差为±0.2 μm。

关 键 词: 涡轮机叶片; 薄层活化法; 磨损; 测量技术;

中图分类号: TK263.3 文献标识码: A

1 前 言

涡轮机叶片的磨损直接影响涡轮机的性能、可靠性和寿命。船用燃气轮机叶片涂层磨损后, 叶片的基体材料在燃气轮机高温烟气产生的近 1 000 ℃的环境中所引起的高温腐蚀和高温蠕变会严重影响机组的可靠性和寿命。船用汽轮机工作在高湿度蒸汽中的叶片, 长期受水滴的高速冲蚀, 极易受损, 因此准确而连续地测量涡轮机叶片的磨损程度, 对研究涡轮机叶片结构设计、材料选择、腐蚀等问题, 以及对提高船用涡轮机的可靠性、故障预告、故障原因分析都有十分重大的意义。

涡轮机叶片在正常工作条件下仅发生微量磨损, 其磨损表面被机组结构遮盖而难以接触到, 采用称重等常规测量技术很难准确测定其在短时间工作过程中的磨损状态, 在这种情况下, 利用带电粒子活化原理开发的薄层活化技术(简称 TLA)就成为监测磨损腐蚀的强有力的工具。从 20 世纪 70 年代初期开始, 美国、英国、德国、日本等发达国家就已采用带电粒子表层活化技术精确测定材料的磨损, 目前已广泛应用于石油、能源动力天然气输送、汽车、锅炉、交通运输、化工、电力等行业, 我国的薄层活化技术研究应用则进展迟缓, 许多行业对此都很陌生[1~4]。

作者和其他研究人员采用薄层活化法, 并于 1999 年在华东船舶工程学院搭载汽轮机叶片抗蚀研究热态试验台, 离线检测镍基自熔合金粉末涂层熔覆叶片、1Cr13 激光相变淬火叶片、司太立合金叶片试样的磨损情况, 在线监测 1Cr13 激光相变淬火叶片、司太立合金叶片试样的冲蚀过程, 获得了满意的结果。

2 磨损测量方法

2.1 薄层活化法的原理

带电粒子一般是指质子(p)、氘核(d)及 α 粒子等。当加速器产生的带电粒子轰击材料表面时, 在被轰击的区域内引起核反应, 结果在材料的局部表面形成很薄的放射层, 厚度与能量有关, 可根据测量需要进行控制。辐照后的材料, 其表面由于放射性示踪物的自然衰变和磨损损失, 使放射性强度随着辐射出的 γ 射线逐渐减弱, 经过半衰期校正后, 测量放射性示踪物活度的变化就可换算出零件表面的磨损量。

零件辐照终止时, 厚靶的放射性活度由下式确定:

$$A=YIt\left(\frac{1-e^{-\lambda t}}{\lambda t}\right) \tag{1}$$

式中: Y—厚靶产额, Bq/(μA·h); A—厚靶放射性活度, Bq; I—辐照电流, μA; t—辐照时间, h; λ—靶核衰变常数, h^{-1}。

材料表面层形成的各种放射性核素按复杂规律沿深度分布。理想情况下活化层只产生一种主要的放射性核素, 放射性核素沿深度的分布可用下式表示:

$$N=\frac{A_x}{A_0}\times 100\% \tag{2}$$

式中: A_0—活化层未经磨损的总放射性活度, Bq; A_x—同一区域中磨去厚度为 x 后的剩余放射性活度, Bq; x—零件磨损厚度, μm; N—剩余放射性强度的百分数。

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作者简介: 齐宏伟(1966—), 男, 河南偃师人, 哈尔滨·第七〇三研究所高级工程师.

2.2 辐照装置

加速器产生的带电粒子束，通过准直孔控制零件表面活化区的位置和大小，选用不同厚度和材料的吸收片，调整带电粒子的入射能量值。用束流积分仪测量束流大小，用铝板作准直孔，铁箔作带电粒子的吸收片。零件辐照时用专门夹具定位，保证每个叶片辐照位置相同。图 1 为辐照装置示意图。

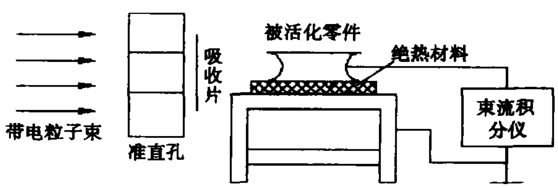

图 1 辐照装置示意图

2.3 测量对象

试验测试对象为镍基自熔合金粉末涂层熔覆叶片、1Cr13 激光相变淬火叶片、司太立合金叶片。试验过程就是测量叶片上指定的活化区域的冲蚀变化。叶片活化区域如图 2 所示（图中尺寸单位是 mm）。3 种叶片的化学成份见表 1～表 3。

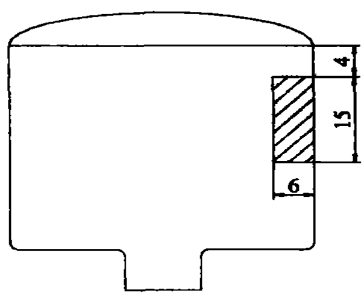

图 2 叶片活化区域示意图

表 1 镍基自熔合金粉末涂层熔覆叶片化学成份 （%）

Si	Ni	Cr	Fe	W	B	C
3.50～5.50	45～54	15～18	≤14	9.00～12.0	3.50～4.50	0.90～1.10

表 2 司太立合金叶片化学成份 （%）

Co	Cr	W	Ni	Fe	Mn	Si	C	S
51～62	28～32	3.5～5.5	1.25～3	≤3.00	0.5～2	0.5～2	0.9～1.4	≤0.03

表 3 1Cr13 激光相变淬火叶片化学成份 （%）

Fe	Cr	Mn	Si	Ni	C
≥83	11.5～13.5	≤1.00	≤1.00	≤0.60	≤0.15

由表 1～表 3 可知，这些合金组成成份复杂，当受到带电粒子辐照后，每种元素都可能产生核反应，形成各种放射性活素，相互干扰。为此采取 5 种措施：(1)试验选择的主测核素半衰期足够长（本试验主测核素 Fe、Cr 的半衰期分别为 270 d 和 312 d）；(2)叶片在辐照后搁置一周或更长时间，使杂质元素产生的短寿命放射性核素自然衰减掉；(3)两种主测的核素放射性能量差别尽可能大；(4)选用能量分辨率高的探测器，当两种射线能谱峰位可以分开时，通过确定“道宽”将其分开；(5)在线监测 1Cr13 激光相变淬火叶片、司太立合金叶片试样的冲蚀过程时，采用净面积法和计算方法解决同时监测两种不同材料磨损状况时出现相同放射性同位素的干扰问题。

2.4 辐照参数的选择

通过查阅文献[1～2]，确定以 Fe、Cr 为镍基自熔合金粉末涂层熔覆叶片、1Cr13 激光相变淬火叶片、司太立合金叶片的主要核反应元素。所选择的主要辐照参数见表 4。

表 4 辐照参数表

核反应	丰度/%	辐照粒子能量 /MeV	束流/μA	辐照时间 /h	厚靶产额 /Bq·(μA·h)$^{-1}$	半衰期/d	主要 γ 射线 /MeV
$^{56}Fe(d, n)\rightarrow^{57}Co$	91.7	$Ed=9$	1.5	1.5	1.37×10^5	270	0.122
$^{53}Cr(d, n)\rightarrow^{54}Mn$	9.5	$Ed=9$	1.5	3.5	—	312	0.834

注：在进行离线测试时，对镍基自熔合金粉末涂层熔覆叶片的辐照能量 $Ed=15.3$ MeV。

2.5 测量装置

测量仪器由探测器(GDB44F)、探测器的屏蔽铅套、定位装置、主放大器、计算机数据采集处理系统组成。在进行试验时，探测器(GDB44F)、探测器的屏蔽铅套和定位装置安装在涡轮机叶片冲蚀试验台上，主放大器和计算机数据采集处理系统安装在试验室旁边的测控室内。

2.6 定量方式

制作定度曲线的目的就是依据该曲线把活度转变成磨损深度。本试验定度曲线的制作是以 1Cr13 材料为基体材料，经能量 $Ed=9$ MeV 的氘核（d）辐

照后, 以 Fe 元素为主测对象, 用腐蚀法进行逐层剥离, 用电感测厚仪对产生的核素 ^{57}Co 深度进行测量, 建立如图 3 所示的定度曲线, 并依据文献[2], 通过理论计算确立定量方式。从图 3 可看出, N 与 x 在 0 ~100 μm 范围内呈线性关系, 理论计算的线性分布辐照深度也是 100 μm, 两者相符。

同理, 在 $Ed=9$ MeV 条件下辐照, 以 Cr 元素为主测对象, 其供计算的线性深度为 82 μm。

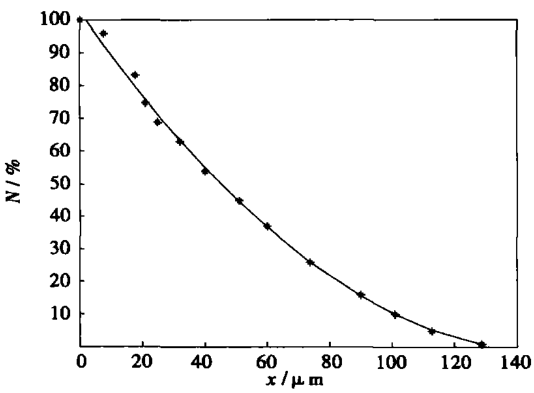

图 3　定度曲线

3　试　验

测试试验分两个阶段, 第一阶段离线检测镍基自熔合金粉末涂层熔覆叶片、1Cr13 激光相变淬火叶片、司太立合金叶片的汽蚀量; 第二阶段在线检测司太立合金叶片、1Cr13 激光相变淬火叶片的汽蚀量, 为验证在线监测数据的重复性和可靠性, 该阶段试验完整地做两次。离线检测和在线监测结果均与称重法获得的结果进行比较, 以验证两种测试方法的结果是否一致。

3.1　离线热态冲蚀测试试验

3.1.1　试验要求及工况

离线测试的司太立合金叶片, 编号为 12、13; 1Cr13 激光相变淬火叶片, 编号为 21、22; 镍基自熔合金粉末涂层熔覆叶片, 编号为 41、42。叶片按 31 →42→22→13→32→41→21→12 的顺序固定在试验台上专用的封闭工夹具中, 其中电火花强化叶片 31、32 为安装要求所加, 本身不被检测。试验工况条件: 饱和蒸汽压力(工作段入口)为 0.7 ~0.8 MPa; 湿度(工作段入口)为 17%; 工作段(叶片)出口背部温度为 94 ℃; 试验流量(实测)为 700 ~750 kg/h; 叶片冲蚀时间为 53 h。

3.1.2　测量与计算结果

编号 22、42 叶片在试验中冲刷形成缺口, 冲蚀结果及误差计算时将其排除。

表 5　离线热态冲蚀结果

试样编号	活化区冲蚀损失深度/μm	相对标准误差/%	平均值标准误差/μm
12	8.2	0.10	±0.1
13	8.7	0.10	±0.1
21	4.2	0.10	±0.1
41	10.0	0.10	±0.2

表 6　离线热态冲蚀与称重法结果比较

试样编号	试样失重/g	活化区冲蚀/μm	试验后试样状态
12	0.001 8	8.2	表面均匀冲蚀
13	0.002 0	8.7	表面均匀冲蚀
21	0.001 1	4.2	表面均匀冲蚀
22	0.050 0	8.0	尖角处异常冲蚀
31	0.005 4	—	表面均匀冲蚀
32	0.002 6	—	表面均匀冲蚀
41	0.003 1	10.0	表面均匀冲蚀
42	0.028 1	29.2	尖角处异常冲蚀

3.2　在线热态冲蚀测试试验

3.2.1　试验要求及工况

在线热态冲蚀试验为不拆卸装置测量司太立合金叶片和 1Cr13 激光相变淬火叶片上指定区域的冲蚀变化。被测司太立合金叶片, 试样编号为 11、14; 激光相变淬火叶片, 试样编号为 23、24。该试验分两步进行, 第一步选用试样 11 和 23, 第二步选用试样 14 和 24。两步试验冲蚀时间均为 53 h。试验分两步的目的不仅是检验薄层活化技术对叶片冲蚀量测量与离线测量结果进行对比情况, 还可以了解叶片在指定工况条件下两种叶片在孕育期至稳定期间热态冲蚀的变化情况。叶片按 34→44→15→25→33 →43→11→14→23→24 顺序固定在试验台上专用的封闭工夹具中, 其中, 司太立合金叶片 15、激光相变淬火叶片 25、电火花强化叶片 33 和 34、镍基自熔合金粉末涂层熔覆叶片 43 和 44 均为安装要求所加, 本身不被检测。试验工况条件: 饱和蒸汽压力(工作段入口)为 0.7 ~0.8 MPa; 湿度(工作段入口)为 17%(第一次)、14%(第二次); 工作段(叶片)出口背部温度为 94 ℃; 试验流量(实测)为 700 ~750 kg/h; 叶片冲蚀时间为 53 h。

3.2.2　测量与计算结果

试验结果见图4、表7、表8和表9,表9中的12、13、21、41为离线测量结果。

表7 第一次试样活化区累计冲蚀量在线测量结果

试样编号	冲蚀时间/h 3.7	11.75	20.25	28.75	37	45	53	相对标准误差/%	平均值标准误差/μm
11	0.2	3.77	6.15	9.35	9.92	10.33	10.82	0.14	±0.1
23	0.0	1.4	2.7	4.3	4.6	4.8	5.1	0.20	±0.2

注:试样累计冲蚀量单位为μm。

表8 第二次试样活化区累计冲蚀量在线测量结果

试样编号	冲蚀时间/h 8	17	26	34	40	48	53	相对标准误差/%	平均值标准误差/μm
14	2.86	5.0	6.56	7.46	8.4	9.31	9.84	0.14	±0.1
24	1.0	1.6	2.2	2.8	3.2	3.4	3.6	0.20	±0.2

注:试样累计冲蚀量单位为μm。

表9 热态冲蚀试验53 h后试样冲蚀量平均值

试样编号	试样失重/g	活化区冲蚀深度/μm	平均失重/g	活化区平均冲蚀深度/μm
12	0.001 8	8.2	0.002 2	9.39
13	0.002 0	8.7		
11	0.002 7	10.82		
14	0.002 4	9.84		
21	0.001 1	4.2	0.001 1	4.30
23	0.001 3	5.1		
24	0.001 0	3.6		
31	0.005 4	—	0.004 0	—
32	0.002 6	—		
41	0.003 1	10.0	0.003 1	10.0

注:剔除异常冲蚀试样22和42。

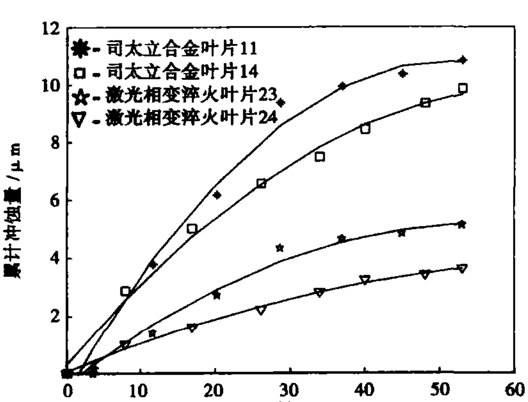

图4 热态冲蚀试样累计冲蚀量趋势图

3.3 试验结果分析

(1)测试结果表明,1Cr13激光相变淬火叶片抗冲蚀性能优于司太立合金叶片和镍基自熔合金粉末涂层熔覆叶片,可为选择涡轮机叶片表面处理抗蚀方法提供依据;

(2)薄层活化法与称重法比较,结果一致;

(3)从图4可看出,薄层活化法的两次在线检测具有良好的稳定性和重复性。

4 结 论

(1)用薄层活化法,对涡轮机叶片样件热冲蚀试验进行了离线和在线(重复两次)测量与监测,测量平均值标准误差为±0.2 μm;

(2)用薄层活化法监测叶片热冲蚀,不受冲蚀流体介质性质的影响,克服了用称重法检查叶片失重,由于蒸汽结垢而影响失重分析精度的缺陷;

(3)用薄层活化法在线监测两种叶片的冲蚀过程,试验需53 h即可精确测量磨损量,若用常规的称重法进行试验,为保证试验精度,需要数百小时以上,两者相比,试验时间明显缩短;

(4)叶片冲蚀试验表明1Cr13材料表面激光淬火比贴司太立合金片具有更高的耐磨(蚀)性。

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(辉 编辑)

pacity increased by 2% to 8%. In this connection the gas turbines in Guangzhou City enjoy the maximum potential for performance improvement. As assessed from the aim of achieving a same increase in the power generation capacity, the installation of a cooling system at the inlet of gas turbines can contribute to a better cost-effectiveness than the case of installing new gas turbine units. **Key words**: gas turbine, inlet air cooling, cost-effectiveness

汽轮机调节阀设计的新思路= **New Ideas for the Design of Steam Turbine Regulating Valves**[刊,汉]/XIANG Xiao-wei, MAO Jing-ru, SUN Bi (State Key Laboratory of Multi-phase Flows in Power Engineering and Turbo-machinery Research Institute under the Xi'an Jiaotong Univeristy, Xi'an, China, Post Code: 710049)// Journal of Engineering for Thermal Energy &Power. — 2006, 21(3). —235~238

On the basis of analyzing currently available design methods of steam turbine regulating valves, the shortcomings of these methods are pinpointed and a new approach for designing the regulating valves is proposed. The new design method includes a numerical computation step. Through a numerical simulation of the flow field of the regulating valves, detailed flow information inside the valves is identified. On this basis, all the irrational factors in the flow field can be detected and with the adoption of proper measures the internal flow field structure improved and optimized to attain the aim of enhancing the aerodynamic performance of the valves. Thereafter, a model experiment can be conducted of the optimized valve followed by a final completion of the valve design. In addition, a calculation method for the three-dimensional flow field of the regulating valves was studied. On the basis of the new approach that the flow field can be optimized based on the numerical calculation proposed in the new design method of valves, a numerical calculation was performed of a specific calculation example. In the light of the existing problems in the flow field, an appropriate adjustment has been undertaken of the valve profile, thus improving its aerodynamic performance. **Key words**: regulating valves of steam turbines, design method, three-dimensional flow field of regulating valves

基于 CFD 的船舶自流冷却系统进水口形式优化= **Optimization of the Types of Water Inlets in Marine Scoop Cooling Systems Based on CFD (Computational Fluid Dynamics)**[刊,汉]/GAO Wei, MIAO Hui, HUANG Shu-hong, et al (Energy Source and Power Engineering School under the Central China University of Science and Technology, Wuhan, China, Post Code: 430074)// Journal of Engineering for Thermal Energy &Power. — 2006, 21(3). —239~244

The structure of water inlets of a marine scoop cooling system has a significant effect on the navigation of ships and the cooling efficiency of condensers. A numerical calculation is conducted for different types of water inlets of marine scoop cooling systems by the use of software Fluent and through the adoption of a standard $k-\varepsilon$ model. The flow characteristics of different types of water inlets are analyzed from such aspects as flow rate, navigation drags and the impact of wake flow fields. The results show that with a same tube diameter, the straight tube inlet can provide a relatively large flow rate and cause a minimal effect to the external flow field. Meanwhile, the extended length of the water inlets can directly influence the flow rate and the magnitude of navigation drags. However, the impact to the wake flow is closely related to water outlets. Hence the design of water inlets should be conducted in conjunction with that of water outlets. **Key words**: scoop cooling system, type of water inlets, numerical simulation, wake flow field

涡轮机叶片磨损测量技术试验研究= **Experimental Study of Measurement Technology to Determine the Wear-and-tear of Turbine Blades**[刊,汉]/QI Hong-wei, YANG Jia-dong, TIAN Dian-juan, et al (Harbin No. 703 Research Institute, Harbin, China, Post Code: 150036)// Journal of Engineering for Thermal Energy &Power. — 2006, 21(3). —245~248

The thin-layer activation method is a kind of nuclear method for the dynamic and qualitative measurement of wear-and-tear of specified parts and components with no need for system disassembly. This method features high sensitivity, an ability to perform on-line detection, and low radioactivity etc. The working principles and relevant techniques of the thin-layer activation method are described. Its application to the on-line and off-line measurement of wear of turbine blades has made it possible to realize an off-line monitoring of cavitation-caused wear for three kinds of turbine blades and an on-line monitoring of same at specified locations for two kinds of turbine blades. A detailed test and detection procedure is given. Through tests lasting 53 hours, the worn-out mass actually measured of the blades is identical to that obtained by using a weighting method. The standard error of average measured values is ±0.2 μm. **Key words**: turbine blade, thin layer activation method, wear

对旋叶栅级间内流干涉的数值研究＝**Numerical Study of Interference of Inter-stage Flows in a Counter-rotating Cascade**[刊, 汉]/XIAO Peng, WANG Jun (College of Energy Sources and Power Engineering under the Central China University of Science and Technology, Wuhan, China, Post Code: 430074)// Journal of Engineering for Thermal Energy & Power. — 2006, 21(3). —249～254

With a whole counter-rotating axial fan serving as an analytic model and through the use of software Fluent and the adoption of SIMPLE algorithm, conducted was a numerical simulation of interference flows between two stages of moving blades in the model. This has been accomplished after solving a full three-dimensional Reynolds time-averaged $N-S$ equation. By combining the numerical simulation results obtained from a steady flow analysis with the flow characteristics of the counter-rotating fan, the flow field distribution of stream surfaces in different circumferential planes S1 and different radial planes S3 in the two stage impeller of the counter-rotating axial fan was given and the interference phenomenon and mechanism of two stages of the counter-rotating fan has been revealed qualitatively and quantitatively. It has been found that in the inter-stage flow field between counter-rotating impellers, relatively speaking, the wake interference effect of the front-stage impeller is stronger than that of the rear stage impeller under the action of potential energy. **Key words**: counter rotating, cascade, numerical simulation, interference

后置蜗壳斜流叶轮内部射流－尾迹数值研究＝**A Numerical Study of the Jet-flow Wake in the Oblique Flow Impeller of a Rear-mounted Volute Housing**[刊, 汉]/CHU Wu-li, YANG Yong, WU Yan-hui, et al (Power and Energy Source College under the Northwest China Polytechnical University, Xi'an, China, Post Code: 710072)// Journal of Engineering for Thermal Energy & Power. — 2006, 21(3). —255～258, 263

A Fine/Turbo module of commercial software Numeca was used to conduct the whole-machine calculation for an oblique flow blower incorporating an oblique flow impeller and a volute housing as an integrated whole. Moreover, on the basis of having achieved a relatively good agreement with the already available test data, a detailed numerical analysis is performed of its inner flow field, which confirms that inside the oblique flow impellers, there also exist classic jet-flow wake patterns specific to a centrifugal impeller. The research results show that due to a highly nonsymmetrical nature of the volute housing, the jet flow-wake inside various impellers also features totally different patterns. A further study indicates that the basic reason leading to the emergence of this phenomenon lies in the presence of a nonsymmetrical volute housing, which changes the blade-tip leakage flow at the top of the impellers. **Key words**: oblique flow impeller, volute housing, wake/jet flow, blade-tip leakage flow

总压畸变对小型风扇气动影响的数值模拟＝**Numerical Simulation of the Impact of Total-pressure Distortion on the Aerodynamic Performance of Small-sized Fans**[刊, 汉]/ SUN Peng, FENG Guo-tai (Energy Source College under the Harbin Institute of Technology, Harbin, China, Post Code: 150001), KUI Dong-wei (Harbin Vocational Col-