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火电厂耐热钢承压部件的蠕变损伤研究

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摘　要: 针对火电厂中蒸汽管道与汽包一类承压部件常用耐热钢材, 在经历长时间高温高压作用后, 处于蠕应变Ⅲ阶段过程时, 发生非线性局部化(大变形)蠕变损伤问题, 给出损伤本构描述, 提出非线性局部化蠕变损伤本构模型及其数值变分原理与有限元离散化形式, 从而形成另一种弹塑性蠕变损伤理论与数值变分新方法。

关　键　词: 耐热钢; 承压部件; 非线性局部化; 蠕变损伤理论

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1　研究耐热钢承压部件的非线性局部化大变形蠕变损伤问题的意义

近年来, 如何解决累计运行超过 20×10^4 h 的大、中型汽轮发电机组中的承压部件(如各种蒸汽管道、汽包、联箱、再热器等)的剩余寿命、力学性能、材质性状和衰变特性一类抗蠕变破坏能力的关键技术问题, 是火电厂寿命管理和金属监督方面的重要课题。这一普遍存在的累计运行超过 20×10^4 h(或 24 年)的大、中型汽轮发电机组中, 各种蒸汽管道与汽包一类承压部件, 以及已受损伤老化的耐热钢材, 概括说基本上已处于钢材蠕变曲线第 Ⅲ阶段了, 其突出的宏观特征是: 表现出显著的蠕变与塑性大变形, 它在几何与物理上都是非线性的; 具有明显的损伤局部件与非均匀性, 从沿晶界滑移发展成微空穴, 继而发展成蠕变空洞, 而且不断扩展连接成宏观裂纹。针对这种情况, 引入现代固体力学与高温蠕变力学中发展前沿领域的连续损伤力学(CDM)的概念、理论与方法, 来研究非线性局部化大变形蠕变损伤问题, 给出弹塑性损伤本构描述, 提出非线性局部化蠕变损伤本构模型及其数值变分原理与有限元离散化形式, 从而形成大变形下弹塑性蠕变损伤理论与数值变分新方法。无疑, 将为迄今至 2010 年期间, 一大批运行累计超过 20×10^4 h 的超期服役大、中型机组中各种承压部件, 其剩余寿命评估、材质衰变劣化程度评定和抗蠕变与承载能力的数值计算等一系列科学论证工作, 提供解析的力学理论与方法, 其经济与社会效益将会是巨大的。

2　非线性局部化大变形蠕变损伤过程的本构描述

如果从耐热钢类金属材料的微观结构与蠕变损伤的机理来看, 工程中实际的蠕变损伤过程, 存在着明显的非均匀性和局部性。由文献[1] 了解到, 近年来提出一种能够描述这种非均匀性与局部性的所谓非线性局部化蠕变损伤理论方法。其具体作法是引入参数 β 与 γ 分别描述材料受损衰变时的损伤非均匀性和局部性。对于单轴蠕变损伤问题, 提出的非线性局部化蠕变损伤方程为:

$$\dot{\varepsilon}^c=\overline{q}(\sigma,\overline{D})=B\sigma^n[(1-\beta)+\beta(1-\frac{\overline{D}}{\beta})^{-n}]\quad(1)$$

$$\dot{\overline{D}}=\overline{h}(\sigma,\overline{D})=\beta\gamma\frac{A}{\varphi+1}\frac{\sigma^P}{(1-\frac{D}{\beta})\varphi}\quad(2)$$

$$\overline{D}_\sigma=\beta[1-(1-\gamma)^{\frac{1}{\varphi+1}}]\quad(3)$$

式中: B、n、A、p、φ 均为高温蠕变材料常数是通过蠕变试验结果的拟合而确定的; β 与 γ 分别为描述材料损伤非均匀性与局部性的两个参数, 也是通过蠕变试验测定的试验数据拟合确定; $\overline{D}_\sigma$ 为材料的平均化损伤程度临界值; $\overline{D}$ 为材料整体平均损伤变量。

对于在常外载 σ^0 等于常数下的高温单轴蠕变损伤问题, 其唯象学蠕变损伤理论中 $k-R$ 蠕变损伤方程为[2]:

$$\dot{\varepsilon}^c=q(\sigma,D)=B[\frac{\sigma}{(1-D)}]^n\quad(4)$$

$$\dot{D}=h(\sigma,D)=\frac{A}{(\varphi+1)}\frac{\sigma^p}{(1-D)^\varphi}\quad(5)$$

式中: B、n、A、p、φ 同上所述, σ 为单轴应力。

严格来说, 由于任何金属构件的蠕变损伤失效,

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都是伴随着塑性变形的发展而演化的过程。因此，处理蠕变损伤应该进行全耦合的弹塑性蠕变损伤分析，基于此给出全部的非线性局部化蠕变损伤本构关系如下[3]：

$$\mathrm{d}\sigma_{ij} = \overline{E}_{ijkL}\mathrm{d}\varepsilon^{c}_{kL} - \frac{\sigma^{0}_{ij}}{(1-D_0)}\mathrm{d}D \quad (6)$$

$$\mathrm{d}\varepsilon_{ij} = \mathrm{d}\varepsilon^{e}_{ij} + \mathrm{d}\varepsilon^{p}_{ij} + \mathrm{d}\varepsilon^{c}_{ij} \quad (7)$$

$$\mathrm{d}\varepsilon^{p}_{ij} = \lambda^{p}\frac{\partial g}{\partial\sigma_{ij}} \quad (8)$$

$$f(\overline{\sigma}_{ij}, \varepsilon^{p}_{ij}) \leqslant 0 \quad (9)$$

$$\lambda^{p}\begin{cases} > 0 & \text{当 } f = 0 \quad \text{(对应于塑性加载)} \\ = 0 & \text{当 } f < 0 \quad \text{(对应于弹性加载或卸载)} \end{cases} \quad (10)$$

$$\dot{\varepsilon}^{c}_{ij} = \overline{q}_{ij}(\overline{\sigma}_{ij}, \overline{D}) \quad (11)$$

$$\overline{D} = \overline{h}(\overline{\sigma}_{ij}, \overline{D}) \quad (12)$$

$$\varepsilon^{c}_{ij}\big|_{t=0} = 0 \quad (13)$$

$$\overline{D}\big|_{t=0} = 0 \quad (14)$$

$$\overline{D}_{\sigma} = \beta[1 + (1-\gamma)^{\frac{1}{\varphi+1}}] \quad (15)$$

式中：$\mathrm{d}\sigma_{ij}$ 为柯西名义应力张量的增量；$\overline{E}_{ijkL}$ 为具有损伤效应的弹性系数张量；$\mathrm{d}\varepsilon^{c}_{ij}$、$\mathrm{d}\varepsilon^{c}_{kL}$ 为蠕变应变增量；$\mathrm{d}\varepsilon_{ij}$ 为总应变增量，$\mathrm{d}\varepsilon^{e}_{ij}$ 为弹性应变增量；$\mathrm{d}\varepsilon^{p}_{ij}$ 为塑性应变增量；f 为屈服函数；g 为塑性势函数；λ^{p} 为塑性流动因子；$\overline{q}_{ij}$ 为表征蠕变规律的蠕变方程；$\overline{h}$ 为表征损伤规律的损伤方程。

上述本构关系式都是高度非线性方程，绝大部分又是自变函数的隐式关系，而且它们之间还存在非独立关系，这是很不利于处理的。基于文献[3] 中提出的数学处理方法，对上述本构关系方程所作数学处理是，分别对 $f(\overline{\sigma}_{ij}, \varepsilon^{p}_{ij})$、$\overline{q}_{ij}(\overline{\sigma}_{ij}, \overline{D})$、$\overline{h}(\overline{\sigma}_{ij}, \overline{D})$ 作一阶展开，然后经代换整理可得到非线性局部化蠕变损伤理论的状态控制方程组为：

$$\overline{\xi}^{(1)}_{ijkL}\mathrm{d}\varepsilon_{kL} + \overline{\eta}^{(1)}_{ij}\mathrm{d}D + \overline{\tau}^{(1)}_{ij}\lambda^{p} + \overline{\rho}^{(1)}_{ijkL}\lambda^{c}_{kL} + \overline{\beta}^{(1)}_{ij} = 0 \quad (16)$$

$$\overline{\xi}^{(2)}_{ij}\mathrm{d}\varepsilon_{ij} + \overline{\eta}^{(2)}\mathrm{d}D + \overline{\tau}^{(2)}\lambda^{p} + \overline{\rho}^{(2)}_{ij}\lambda^{c}_{ij} + \overline{\beta}^{(2)} = 0 \quad (17)$$

$$\overline{\xi}^{(3)}_{ij}\mathrm{d}\varepsilon_{ij} + \overline{\tau}^{(3)}\lambda^{p} + \overline{\rho}^{(3)}_{ij}\lambda^{c}_{ij} + \overline{\beta}^{(3)} + \upsilon = 0 \quad (18)$$

$$\upsilon \cdot \lambda^{p} = 0,\ \lambda^{p} \geqslant 0,\ \upsilon \geqslant 0 \quad (19)$$

其中：$\overline{\xi}^{(k)}$、$\overline{\eta}^{(k)}$、$\overline{\tau}^{(k)}$、$\overline{\rho}^{(k)}$、$\overline{\beta}^{(k)}$（$k = 1, 2, 3$）的计算表达式同弹塑性蠕变损伤问题的对应表示式[3]，只是将原蠕变损伤函数 q_{ij} 与 h 换成 $\overline{q}_{ij}$ 和 $\overline{h}$ 即可。

3　非线性局部化蠕变损伤理论中的数值变分方法

本问题的势能泛函形式，同弹塑性蠕变损伤问题中所构造的势能泛函[3] 完全一样为：

$$\Pi_{\mathrm{III}}(\mathrm{d}\varepsilon_{ij}, \mathrm{d}u_i, \mathrm{d}D, \lambda^{p}, \lambda^{c}_{ij}) = \int_{\Omega}\{\frac{1}{2}\overline{E}_{ijkL}\mathrm{d}\varepsilon_{ij}\mathrm{d}\varepsilon_{kL} - \lambda^{p}\overline{E}_{ijkL}\frac{\partial g}{\partial\sigma_{ij}}\mathrm{d}\varepsilon_{kL} - \lambda^{c}_{ij}\overline{E}_{ijkL}\mathrm{d}\varepsilon_{kL} - \frac{\mathrm{d}D}{(1-D_0)}\sigma^{0}_{ij}\mathrm{d}\varepsilon_{ij}\}\mathrm{d}\Omega - [\int_{\Omega}\mathrm{d}b_i\mathrm{d}u_i\mathrm{d}\Omega + \int_{S_p}\mathrm{d}\overline{p}_i\mathrm{d}u_i\mathrm{d}S] \quad (20)$$

其变分原理的基本思路是，对于任一时刻 t，就时间增量 $\mathrm{d}t$ 的范围内，即$[t, t+\mathrm{d}t]$，在所有满足应变位移关系与几何边界条件的可能位移增量场中，其真实解使得泛函式(20) 在状态控制方程式(16) ~ 式(19) 以及初始条件式(13) 与式(14)，甚至临界损伤式(15) 的控制下取总体最小，其中 $\mathrm{d}\varepsilon_{ij}$（或 $\mathrm{d}u_i$）是自变量函数，λ^{c}_{ij}、λ^{p} 与 $\mathrm{d}D$ 是状态控制参变量，不参加变分。该思路是现代变分原理中不对参变量求变分的关键思想。

同理，采用推证变分原理成立的方法[3]，对式(20) 求变分后并经代换整理可得：

$$\delta\Pi_{\mathrm{III}} = \int_{\Omega}[\mathrm{d}\sigma_{ij}\ \ \delta(\mathrm{d}\varepsilon_{ij}) - \mathrm{d}b_i\ \ \delta(\mathrm{d}u_i)]\mathrm{d}\Omega - \int_{S_p}\mathrm{d}\overline{p}_i\ \ \delta(\mathrm{d}u_i)\mathrm{d}S \quad (21)$$

再应用分部积分法，并考虑到在边界 S_u 上有 $\delta(\mathrm{d}u_i) = \delta(\mathrm{d}\overline{u}_i = 0)$，故式(21) 右端的第一项积分可改写成

$$\int_{\Omega}\mathrm{d}\sigma_{ij}\ \ \delta(\mathrm{d}\varepsilon_{ij})\mathrm{d}\Omega = \int_{S_p}\mathrm{d}\sigma_{ij}\eta_j\ \ \delta(\mathrm{d}u_i)\mathrm{d}S - \int_{\Omega}\mathrm{d}\sigma_{ij,j}\ \ \delta(\mathrm{d}u_i)\mathrm{d}\Omega \quad (22)$$

将式(22) 代入式(21) 中，有：

$$\delta\Pi_{\mathrm{III}} = -\int_{\Omega}[\mathrm{d}\sigma_{ij,j} + \mathrm{d}b_i]\ \ \delta(\mathrm{d}u_i)\mathrm{d}\Omega + \int_{S_p}[(\mathrm{d}\sigma_{ij}\eta_j - \mathrm{d}\overline{p}_i)\ \ \delta(\mathrm{d}u_i)\mathrm{d}S \quad (23)$$

令 $\delta\Pi_{\mathrm{III}} = 0$，且由于 $\delta(\mathrm{d}u_i)$ 的任意性和足够小的特点，可求得平衡方程 $\mathrm{d}\sigma_{ij,j} + \mathrm{d}b_i = 0$（在 Ω 中）和边界条件 $\mathrm{d}\sigma_{ij}\eta_j - \mathrm{d}\overline{p}_i = 0$（在 S_p 上）。这充分证明所构造的势能泛函式(20) 满足平衡方程与边界条件，同时还可证实具有损伤效应时，单元的应力可用有效应力 $\overline{\sigma}_{ij}$ 表达，但单元的有效面积却因损伤产生孔洞效

应而减小$(1-D)$倍，故损伤状态下的应力平衡方程为 $\bar{\sigma}_{ij,j}(1-D)+b_i=0$，将它代入上述平衡方程中可得 $\bar{\sigma}_{ij,j}+b_i=0$，该式表明是与无损伤情况下的平衡方程一样。再进一步取 $\delta^2\Pi_{\mathrm{III}}\geqslant 0$，则由 $\delta\Pi_{\mathrm{III}}=0$ 导出的状态变量函数 $\mathrm{d}\varepsilon_{ij}$(或 $\mathrm{d}u_i$)，使得 Π_{III} 取总体最小，同时因 Π_{III} 是在状态方程式(16) ~ 式(19)以及初始条件式(13)与式(14)的控制下取其极值的，故在整个过程中也同时满足了蠕变函数式(11)和损伤规律式(12)，这就更充分证明变分原理成立。

具有损伤耦合的非线性局部化蠕变损伤理论的数值变分原理简要归纳如下：

$$\mathop{minimize}\Pi_{\mathrm{III}} \tag{24}$$

$\mathrm{d}\varepsilon_{ij}$(或 $\mathrm{d}u_i$)

受控于：

$$\bar{\xi}^{(1)}_{ijkL}\mathrm{d}\varepsilon_{kL}+\bar{\eta}^{(1)}_{ij}\mathrm{d}D+\bar{\tau}^{(1)}_{ij}\lambda^p+\bar{\rho}^{(1)}_{ijkL}\lambda^c_{kL}+\bar{\beta}^{(1)}_{ij}=0 \tag{25}$$

$$\bar{\xi}^{(2)}_{ij}\mathrm{d}\varepsilon_{ij}+\bar{\eta}^{(2)}\mathrm{d}D+\bar{\tau}^{(2)}\lambda^p+\bar{\rho}^{(2)}_{ij}\lambda^c_{ij}+\bar{\beta}^{(2)}=0 \tag{26}$$

$$\bar{\xi}^{(3)}_{ij}\mathrm{d}\varepsilon_{ij}+\bar{\tau}^{(3)}\lambda^p+\bar{\rho}^{(3)}_{ij}\lambda^c_{ij}+\bar{\beta}^{(3)}+\upsilon=0 \tag{27}$$

$$\upsilon\cdot\lambda^p=0,\ \lambda^p\geqslant 0,\ \upsilon\geqslant 0 \tag{28}$$

$$\lambda^c_{ij}\big|_{t=0}=0,\ D\big|_{t=0}=0 \tag{29}$$

4　耐热钢连续体离散后的有限元形式

为了便于对耐热钢承压部件的非线性局部化蠕变损伤问题进行数值计算，可将耐热钢承压部件连续体 Ω 进行离散化，然后引入有限元插值函数，即：

$$\mathrm{d}u=N_{\mathrm{u}}\delta \tag{30}$$

$$\mathrm{d}\varepsilon=B_{\varepsilon}\delta \tag{31}$$

$$\mathrm{d}D=N_{\mathrm{D}}\alpha \tag{32}$$

$$\lambda^c=B_{\mathrm{c}}K \tag{33}$$

式中：δ为节点位移增量；α为节点损伤值增量；K为节点蠕应变增量；N_u为位移形函数；B_{ε}为应变算子形函数；N_{D}为损伤形函数；B_{c}为蠕应变形函数。

通常对式(25) ~ 式(29)，引入上述插值函数式(30) ~ 式(33)，再通过单元的组装，可将系统的总势能与状态控制方程改写为：

$$\Pi_{\mathrm{III}}(\delta)=\frac{1}{2}\delta^T\bar{K}\delta-\delta^T[\Phi_1\lambda^p+\Phi_2\alpha+\Phi_3K+q] \tag{34}$$

受控于：

$$C_1\delta+U_1\alpha+V_1\lambda^p+W_1K+d_1=0 \tag{35}$$

$$C_2\delta+U_2\alpha+V_2\lambda^p+W_2K+d_2=0 \tag{36}$$

$$C_3\delta+V_3\lambda^p+W_3K+d_3+v=0 \tag{37}$$

$$\upsilon^T\lambda^p=0,\ \lambda^p\geqslant 0,\ \upsilon\geqslant 0 \tag{38}$$

式中：

$\bar{K}=\sum\limits_{e=1}^{n}\int_{\Omega^e}(B_C^TEB_C)\mathrm{d}\Omega=(1-D_0)\times\sum\limits_{e=1}^{n}\int_{\Omega^e}(B_c^TEB_c)\mathrm{d}\Omega=(1-D_0)k$；

$K=\sum\limits_{e=1}^{n}\int_{\Omega^e}(B_\varepsilon^TEB_\varepsilon)\mathrm{d}\Omega$；

$\Phi_1=\sum\limits_{e=1}^{n_1}\int_{\Omega^e}[(\frac{\partial g}{\partial\sigma})^TEB_c]^T\mathrm{d}\Omega$；

$\Phi_2=\sum\limits_{e=1}^{n}\int_{\Omega^e}[\frac{1}{(1-D_0)}(B_C^T\sigma^0N_D)]\mathrm{d}\Omega$；

$\Phi_3=\sum\limits_{e=1}^{n}\int_{\Omega^e}(B_C^TEB_C)\mathrm{d}\Omega$；

$q=\sum\limits_{e=1}^{n}\int_{\Omega^e}(N_u^T\mathrm{d}b)\mathrm{d}\Omega+\sum\limits_{e=1}^{n_2}\int_{S^e}(N_u^T\mathrm{d}\bar{p})\mathrm{d}S$；

$C_1=\sum\limits_{e=1}^{n}\int_{\Omega^e}[B_C^T\xi^{(1)})]\mathrm{d}\Omega$；

$U_1=\sum\limits_{e=1}^{n}\int_{\Omega^e}(N_D^T\eta^{(1)})\mathrm{d}\Omega$；$V_1=\sum\limits_{e=1}^{n_1}\int_{\Omega^e}\bar{\tau}^{(1)}\mathrm{d}\Omega$；

$W_1=\sum\limits_{e=1}^{n}\int_{\Omega^e}(B_c^T\rho^{(1)})\mathrm{d}\Omega$；

$d_1=\sum\limits_{e=1}^{n}\int_{\Omega^e}\bar{\beta}^{(1)}\mathrm{d}\Omega$；$C_2=\sum\limits_{e=1}^{n}\int_{\Omega^e}(B_C^T\xi^{(2)})\mathrm{d}\Omega$；

$U_2=\sum\limits_{e=1}^{n}\int_{\Omega^e}(N_D^T\eta^{(2)})\mathrm{d}\Omega$；

$V_2\sum\limits_{e=1}^{n_1}\int_{\Omega^e}\bar{\tau}^{(2)}\mathrm{d}\Omega$；$W_2=\sum\limits_{e=1}^{n}\int_{\Omega^e}(B_c^T\rho^{(2)})\mathrm{d}\Omega$；

$d_2=\sum\limits_{e=1}^{n}\int_{\Omega^e}\bar{\beta}^{(2)}\mathrm{d}\Omega$；

$C_3=\sum\limits_{e=1}^{n_1}\int_{\Omega^e}(B_C^T\xi^{(3)})\mathrm{d}\Omega$；$V_3=\sum\limits_{e=1}^{n_1}\int_{\Omega^e}\bar{\tau}^{(3)}\mathrm{d}\Omega$；

$W_3=\sum\limits_{e=1}^{n_1}\int_{\Omega^e}(B_c^T\rho^{(3)})\mathrm{d}\Omega$；$d_3=\sum\limits_{e=1}^{n_1}\int_{\Omega^e}\bar{\beta}^{(3)}\mathrm{d}\Omega$

由变分原理可知，$\dfrac{\partial\Pi_{\mathrm{III}}}{\partial\delta}=0$ (39)

再由式(34)可得：

$$\bar{K}\delta-\Phi_1\lambda^p-\Phi_2\alpha-\Phi_3K-q=0 \tag{40}$$

同时加上状态控制方程式(35) ~ 式(38)，就对 δ、α、K、λ^p、υ 进行求解，即方程组为：

$$\begin{cases}\bar{K}\delta-\Phi_1\lambda^p-\Phi_2\alpha-\Phi_3K-q=0\\ C_1\delta+U_1\alpha+V_1\lambda^p+W_1K+d_1=0\\ C_2\delta+U_2\alpha+V_2\lambda^p+W_2K+d_2=0\\ C_3\delta+V_3\lambda^p+W_3K+d_3+v=0\\ v^T\lambda^p=0,\ \lambda^p\geqslant 0,\ v\geqslant 0\end{cases} \tag{41}$$

在式(41)中前四个方程为线性方程，而最后一个为非线性互补方程。虽然式(41)中前四个方程是线性

的，但计算出的 δ、α、k、λ^p、υ 并不满足线性叠加原理，这是由于蠕变损伤问题，实质上是与时间相关的非线性问题，而非线性局部化蠕变损伤是大变形蠕变（在几何与物理上都是非线性的）损伤问题，更是高度非线性的，故矩阵 Φ_1、Φ_2、Φ_3、C_1、C_2、C_3、U_1、U_2、V_1、V_2、V_3、W_1、W_2、W_3、d_1、d_2 和 d_3 在每个时间步 $[t_i, t_{i+1}]$ 都要反复重新计算才行。

5　耐热钢的蠕变试验、局部化理论模型和数值变分计算结果

针对耐热钢 12Cr1MoV 钢在 540 ℃和 2.25Cr1Mo 钢在 550 ℃时的单轴拉伸蠕变试验结果，以及采用非线性局部化蠕变损伤理论模型与数值变分计算结果绘出蠕变曲线和损伤曲线如下：

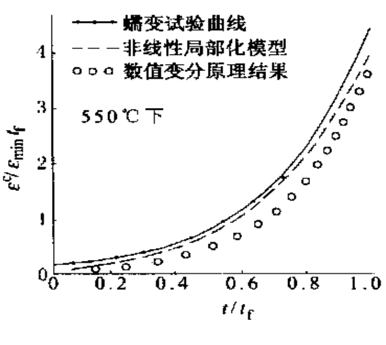

图 1　2.25Cr1Mo 钢在 550 ℃下的蠕变曲线

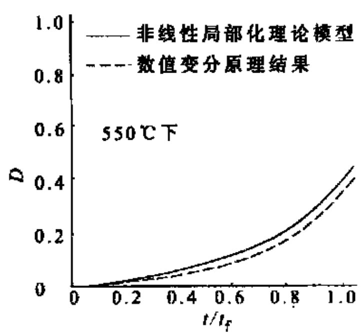

图 2　2.25Cr1Mo 钢在 550 ℃下的蠕变损伤曲线

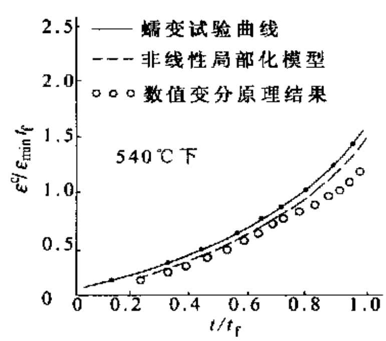

图 3　12Cr1MoV 钢在 540 ℃下的蠕变曲线

在高温单轴拉伸蠕变试验时，考虑在常外载 σ 等于常数下，选用唯象学蠕变损伤理论中 $K-R$ 蠕变损伤方程为式（4）与式（5），非线性局部化蠕变损伤理论模型为式（1）～式（3），对其进行数值变分处理，其三种结果都绘于图 1 ～图 4 中，其中最小蠕应变速率 $\varepsilon_{min}=B^m$；t_f 为失效寿命；归一化蠕应变为 $\varepsilon^c/\varepsilon_{min} t_f$；归一化时间为 t/t_f。

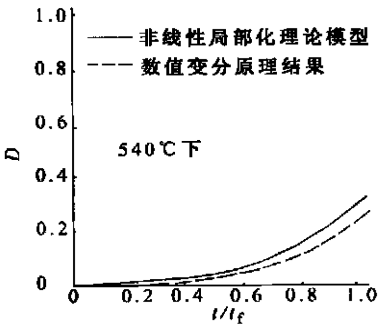

图 4　12Cr1MoV 钢在 540 ℃下的蠕变损伤曲线

6　结论

（1）火电厂中大、中型汽轮发电机组，在额定高温高压参数确定的运行工况下，累计运行超过 20×10^4 h 后，将进入耐热钢材蠕变试验曲线所表征的蠕变Ⅲ阶段，呈现出明显的非线性局部化蠕变损伤的特征，绝大部分蠕变与塑性大变形集中在一局部区域内，在几何与物理上都是非线性的，具有清晰的损伤局部性与非均匀性，诸多微空穴陡然发展成蠕变孔洞并随即形成宏观裂缝。基于此提出了非线性局部化蠕变损伤理论模型如式（1）～式（3），能很好描述耐热钢材高温蠕变试验情况和热能动力工程中实际承压部件的高温蠕变损伤性状，具有很强的广泛实用价值。

（2）本文作者提出的非线性局部化蠕变损伤过程的本构描述模式、方程、数值变分原理与有限元形式，具有广泛的普适性，不仅推动了高温蠕变损伤力学的发展，而且将对粘塑性力学、流变力学、相变力学和非线性力学的发展，提供有益的理论模式与变分新方法。

（3）由于火电厂中任何承压部件的蠕变损伤失效破坏，都是伴随着塑性变形的累积而演化，因此，非线性局部化蠕变大变形损伤问题，实质上也是一种进行全耦合的弹塑性蠕变损伤分析理论。两种耐热钢的高温蠕变试验曲线，同以非线性局部化理论模型及其数值变分计算结果相比较，具有很好的一致性，表明本文提出的非线性局部化理论模型及数值变分方法有很强的科学性、合理性和实用性。

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（辉　编辑）

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With a liquid-phase residual saturation degree Sir being assigned a definition a wet capillary porous media drying-zone is divided into a wet zone and a dry one. On this basis set up was a phase-transformation heat transfer and mass transfer constant-pressure model for the drying process of a wet region with liquid-phase saturation-degree S and temperature T serving as parameters. By using a full-hidden finite difference method a numerical calculation was conducted of the above-cited model. The numerical solution indicates that with the help of the model one can accurately forecast the change of the liquid-phase saturation-degree S and temperature T in the drying process of the wet region. **Key words**: capillary porous media, phase transformation, heat transfer and mass transfer

电磁式在线自动平衡系统及其动平衡方法研究＝**The Study of An On-line Automatic Dynamic Balancing System and Its Dynamic Balancing Method When Used on a Flexible Rotor** [刊, 汉] / WANG Xi-xuan, ZENG Sheng (Chemical Machinery Research Institute under the Zhejiang University, Hangzhou, China, Post Code: 310027) //Journal of Engineering for Thermal Energy & Power. — 2003, 18(1). —53~57

An innovative on-line automatic dynamic balancing system is proposed along with a description of its working principle, construction and dynamic balancing method. The system is equipped with one or more than one automatic dynamic balancing head on the shaft of a rotating machine. The stator of the balancing head is capable of producing a non-contact electromagnetic force to drive the balancing disc installed on a rotating shaft. Each balancing head has two or three balancing discs, each of which has been provided with a balancing block (or called the balancing mass). The total balancing vector as a resultant composed of the balancing masses of the two or three balancing discs can balance the loss of balance of the rotor. The vibration of the shaft and positioning of the balancing discs can be detected by relevant sensors. The balancing disc assumes a single-direction movement mode, which can considerably simplify a control system. The movement principle and procedures of the balancing disc aimed at a dynamic balancing of the rotor are also discussed. The dynamic balancing test has been successfully conducted on an experimental test rig incorporating a flexible rotor. **Key words**: automatic dynamic balancing, on-line dynamic balancing, electromagnetic balancing head

基于免疫进化算法的过热汽温自整定 PID 控制研究＝**A Study of the Immune Evolutionary Algorithm-based Self-tuning PID Control of Superheated Steam Temperature** [刊, 汉] / TAN Ying-zi (Automation Department, Southeastern University, Nanjing, China, Post Code: 210096), SHEN Jiong, LU Zhen-zhong (Power Engineering Department, Southeastern University, Nanjing, China, Post Code: 210096) //Journal of Engineering for Thermal Energy & Power. — 2003, 18(1). —58~62

In accordance with biological immune-system characteristics the authors have come up with a method of self-tuning PID controller parameters on the basis of an immune evolutionary algorithm. The immune evolutionary algorithm has introduced memory cells and features diversity and an anti-body concentration regulation mechanism, ensuring a rapid and stable convergence to attain an overall optimal point. A simulation of the superheated steam temperature control system has demonstrated the validity of the recommended algorithm. **Key words**: immune evolutionary algorithm, PID parameter self-tuning, superheated steam temperature control

火电厂耐热钢承压部件的蠕变损伤研究＝**A Study of the Creep-related Damage of Heat-resistant Steel Pressure Parts of a Thermal Power Plant** [刊, 汉] / GUO Jing (Institute of Power & Mechanical Engineering under the Wuhan University, Wuhan, China, Post Code: 430072), ZHAN Ping (Institute of Urban Construction under the Wuhan University, Wuhan, China, Post Code: 430072), WANG Wen-an (Institute of Civil Engineering under the Wuhan University, Wuhan, China, Post Code: 430072) //Journal of Engineering for Thermal Energy & Power. — 2003, 18(1). —63~66

Heat-resistant steel materials are often used for the pressure parts and components of a thermal power plant, such as steam pipelines. After being subjected to high-temperatures and high-pressures lasting for a long time and with the even-

tual initiation of creep-strain stage III process there will emerge the problem of nonlinear localized (large deformation) creep damage. With reference to the latter the authors have given a damage constitutive description and presented a non-linear localized creep-damage constitutive model along with its numerical variation theory and finite-element discretization form. This has led to the formation of another kind of elastic-plastic creep-damage theory and a new numerical variation method. **Key words**: heat-resistant steel, pressure parts and components, nonlinear localization, creep damage theory

湿压缩对压缩系统失速后瞬态响应的影响分析= **An Analysis of the Influence of Wet Compression on the Post-stall Transient Response of a Compression System** [刊, 汉] / WANG Yu-hui, SUN Yun-feng (College of Power and Nuclear Engineering under the Harbin University of Engineering, Harbin, China, Post Code: 150001), LIU Ming, et al (Harbin No. 703 Research Institute, Harbin, China, Post Code: 150036) // Journal of Engineering for Thermal Energy & Power. — 2003, 18(1). —67～70

A Moore-Greitzer model of a wet compression system was set up, which can be used to analyze the effect of wet compression on the post-stall transient response of a compression system. The simulation results of the model, qualitatively describing the effect of wet compression on the unstable operation performance of the compression system, indicate that under certain conditions the wet compression is conducive to eliminating surge and rotating stall. As a result, the operation stability of the system is enhanced along with an improved performance of the compressor, compression system and gas turbine. **Key words**: wet compression, compressor, compression system

高温过热器壁温测试及计算= **Test and Calculation of the Tube Wall Temperature of a High-temperature Superheater** [刊, 汉] / YU Yan-zhi, TANG Bi-guang (Power Generation Machine College under the Wuhan University, Wuhan, China, Post Code: 430072), LI Shu-lei (Huainan Pinxu Power Generation Co. Ltd., Huainan, Anhui Province, China, Post Code: 232089) // Journal of Engineering for Thermal Energy & Power. — 2003, 18(1). —71～73

Superheater tube explosions resulting from overtemperature is one of the major causes leading to an unscheduled shutdown of thermal power plants. To fully keep track of the situation regarding the superheater tube wall temperature, a real-time acquisition of the tube wall temperatures inside and outside the furnace and their changes was carried out on a 410 t/h super-high pressure boiler. Taking into account the distribution of three-dimensional flue gas temperature and speed, the authors have set up a model for calculating the distribution of the superheater tube-wall temperature inside the furnace and prepared a MATLAB language based three-dimensional visual-display computation program. With the help of this program it is possible to calculate the tube-wall temperature distribution at various locations of the superheater tube rows. Furthermore, one can also obtain a graphic display of the three-dimensional distribution of the flue gas temperature and speed as well as the superheater tube-wall temperatures. The results of a theoretical calculation were found to agree fairly well with those of experiments. **Key words**: superheater, tube wall temperature, boiler, calculation

应用烟方法分析 PFBC—CC 系统的环境影响= **An Analysis of the Environmental Impact of a PFBC-CC (Pressurized Fluidized Bed Combustion Combined Cycle) System by Using an Exergy Method** [刊, 汉] / ZHENG Pu-yan, CAI Ning-sheng, XIAO Jun, QIU Fang-fang (Research Institute of Thermal Energy Engineering under the Southeastern University, Nanjing, China, Post Code: 210096) // Journal of Engineering for Thermal Energy & Power. — 2003, 18(1). —74～77

By using an exergy method a model for the thermal analysis of system emissions and waste heat was set up. Starting from the concept of exergy the environmental impact of emissions is analyzed in general. Furthermore, the impact on environment of a PFBC-CC (pressurized fluidized bed combustion combined cycle) power generation system has also been analyzed. The results of the analysis indicate that the environmental impact of CO_2 emissions and waste heat of the system should not be ignored. The transfer of element S from SO_2 into $CaSO_4$ can drastically reduce the environmental impact of the system. To achieve a more comprehensive analysis of the environmental impact with the help of the exergy method, it