TEORIJSKA I PRIMENJENA MEHANIKA 20, pp 167–176, 1994, 539

ON VISCOPLASTICITY OF IRRADIATED STEELS

M. V. Mićunović

(Received 01.11.1994.)

The irradiation of steels by neutrons appears during many modern technological processes. Experiments promoted division of neutrons into [9] super cool, very cool, thermal, resonant, intermediate, fast, high-energetic and relativistic groups according to their energies. As one of the most important examples we may mention periodic intensive neutron bombardment of the first wall blanket of nuclear reactors. During such a process there appears the class of thermal, resonant, intermediate and fast neutrons where nuclei may be treated as fixed with respect to moving neutrons. This permits application of classical mechanics concepts. From the whole bundle of processes which accompany neutron irradiation we are mainly concerned here with their interaction with dislocations (as microscopic cause of plasticity) as well as voids (microscopic cause of damage like thermal creep). For continuum mechanics type considerations their influence on inelastic constitutive equations is of primary concern. Such an influence is the subject of this paper where we analyze finite thermoplastic strains at time rates which do not allow time independent idealization. Microstructural changes of steel structure are here described by internal variables approach with incompatible strains as opposite to the approach with compatible strains and inelastic memory.

1. Introductory comments on deformation kinematics of continuously damaged steels

Consider a crystalline body, $\mathcal{B}$, with continuous distribution of line and point defects as well as of voids and impurities - Fig.1. Such a body is observable in a family of deformed configurations (ψ_t) and also in an initial reference configuration (κ_0). In configurations (ψ_t) the body is subjected to surface tractions as well as to an inhomogeneous temperature field $\theta(X^K, t)$ where $X^K (K \in \{1,2,3\})$ are material coordinates and t is time. Removing the surface tractions and bringing the temperature to its constant reference value θ_0 which $\mathcal{B}$ has in (κ_0) we attain a partially unloaded configuration (κ_t). In such a configuration dislocations and voids are not removed with the consequence that an equilibrated residual stress

(often named *"back-stress"* and denoted by $\mathbf{B}$) still exists. It is worth noting that, in general, $\mathbf{B}_0$ exists even in (κ_0).

Denoting by $\mathbf{F}$, $\mathbf{F}_E$ and $\mathbf{F}_P$, i.e.

$$\mathbf{F} : (\kappa_o) \to (\psi_t), \quad \mathbf{F}_E : (\kappa_t) \to (\psi_t), \quad \textit{and} \quad \mathbf{F}_P : (\kappa_o) \to (\kappa_t) \tag{1}$$

total, *quasi-thermoelastic* and *quasi-plastic deformation gradient tensor*, respectively, we arrive at the corresponding objective strain measures:

$$2\mathbf{E} = \mathbf{F}^T\mathbf{F} - \mathbf{1}, \tag{2}$$

$$2\varepsilon_P = \mathbf{F}_P^T\mathbf{F}_P - \mathbf{1}, \tag{3}$$

$$\tilde{\varepsilon}_E := \mathbf{E} - \varepsilon_P = \mathbf{F}_P^T\left(\mathbf{F}_E^T\mathbf{F}_E - \mathbf{1}\right)\mathbf{F}_P \equiv \mathbf{F}_P^T\varepsilon_E\mathbf{F}_P \tag{4}$$

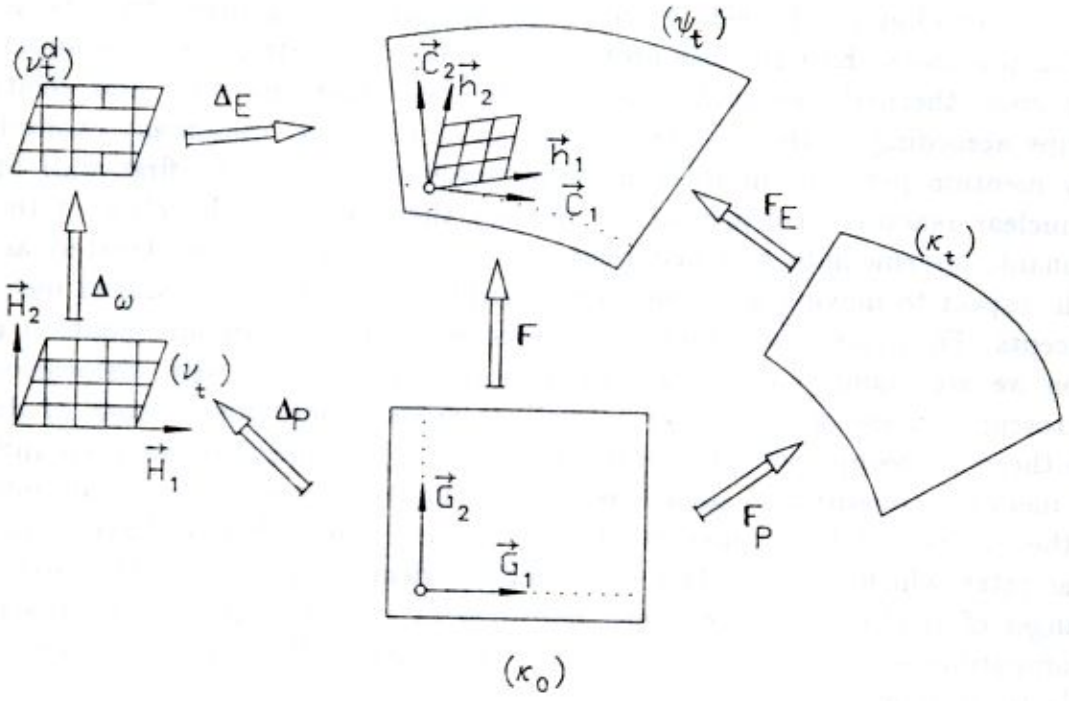

Fig. 1. Basic configurations and corresponding deformations

Another approach to deformation geometry would be to take into account microstructural changes rendering lattice rearrangements. To do this we imagine that (ψ_t) is cut into small volume elements [1] (ν_t^d) relaxed from action of their neighbors with voids but without dislocations. Exhausting voids form these elements we would get the corresponding *"natural state elements"* (ν_t) (already introduced in [2]–[5] and elsewhere). According to this terminology (ν_t^d) - elements might be called *"damaged natural state elements"*. The corresponding mappings - second rank tensors

$$\Delta_P : (\kappa_o) \to (\nu_t), \quad \Delta_\omega : (\nu_t) \to (\nu_t^d), \quad \textit{and} \quad \Delta_E : (\nu_t^d) \to (\psi_t) \tag{5}$$

are *incompatible* and for this reason are called here *plastic*[1], *damage*[2] and *elastic distortions*, respectively. For simplicity in the sequel it is assumed that damage distortion is spherical (somewhere called also "isotropic damage") which means that $\Delta_\omega = (1+\omega)\mathbf{1}$.

Analogously to (3), (4) thermoelastic Lagrangean strain is represented by

$$2\mathbf{E}_E = {\Delta_E}^T \Delta_E - \mathbf{1}, \tag{6}$$

whereas inelastic Eulerian strain accounting for simultaneous damage and plasticity equals:

$$2\mathbf{e}_P = \mathbf{1} - (1+\omega)^{-2} {\Delta_P}^{-T} {\Delta_P}^{-1}. \tag{7}$$

Such two measures are convenient for the formulation of constitutive equations because they are defined with respect to the same reference configuration (ν_t^d). The appropriate corresponding measure of plastic strain time rate again referred to (ν_t^d) is plastic stretching tensor

$$2\mathbf{D}_P = \mathbf{L}_P + \mathbf{L}_P^T \quad (where \quad \mathbf{L}_P = \dot{\Delta}_P {\Delta_P}^{-1}). \tag{8}$$

whose trace corresponds to damage rate i.e. $\mathrm{tr}\mathbf{D}_p = 3\dot{\omega}(1+\omega)^{-1}$.

There has been recently a considerable interest in the literature concerning arbitrary rotations of natural state elements. This item is elaborated in detail in [17].[3] In all cases quasi-thermoelastic and quasi-plastic deformation gradient tensors may be expressed by the following objective microstructural deformation variables ω, Δ_P and $\mathbf{E}_E$ i.e.

$$\varepsilon_E = \varepsilon_E(\omega, \mathbf{E}_E, \Delta_P) \quad and \quad \varepsilon_P = \varepsilon_P(\omega, \Delta_P). \tag{9}$$

2. Evolution of the Process and Constitutive Equations

In formulating a constitutive theory one of essential questions is how to choose constitutive variables and corresponding response functions. If we adopt strain measures (3) and (4), then additional quantities describing inelastic memory are indispensable. In [18] these measures are applied while inelastic history is simply taken into account by two scalars: accumulated plastic deformation path length π and maximum plastic strain distance δ_o from (κ_o) as a measure of *discrete memory* [10], [11] (under tacit assumption that $\delta_m(0) = 0$ in the first

[1] If instead of real crystal configuration (κ_o) an ideal crystal is chosen then the corresponding plastic distortion is not unique. This is promoted in [6] to be *replacement invariance*. Obviously mapping $(5)_1$ is replacement-invariant.

[2] Incompatibility of damage distortion Δ_ω is often neglected in the literature on continuum damage mechanics (cf. eg. [7] where overall closing of voids is assumed to give a fictitious undamaged global configuration).

[3] However, a short comment is worthwhile: making polar decompositions of tensors in (5) we may either choose 1. *isoclinicity* of (ν_t) with the corresponding global ideal crystal [19] 2. elimination of rotation tensor of plastic distortion [17] or 3. elimination of rotation tensor of thermoelastic distortion as made in [20]. The important outcome of all these methods is that only six components of inelastic distortion are mutually independent.

cycle and > 0 during subsequent cycles). These two quantities are determined by the following expressions

$$\dot{\pi} \equiv \|\dot{\varepsilon}_P\| \equiv (\dot{\varepsilon}_P : \dot{\varepsilon}_P)^{\frac{1}{2}} \geq 0 \quad and \quad \delta_m := \max_{\tau \in [t_o, t]} \delta(\tau) \equiv \max_{\tau \in [t_o, t]} \|\varepsilon_P(\tau)\|.$$

where the superposed dot signifies the material time derivative. This approach is convenient for inelastic cycling processes accompanied by neutron irradiation. Some history measures must be introduced due to "blindness" of the method for microstructural changes.

An alternative to this method is to take into account so called *internal variables* replacing in such a way inelastic deformation history by microstructural deformation measures. Such an approach is applied in [9] to rate-independent plasticity of irradiated materials where microstructural measures (6) and $(5)_1$ and scalar dislocation density have been selected as internal variables.

The second approach is adopted here with the following objective (frame indifferent) constitutive variables selected as appropriate to form the set

$$\Gamma = \left\{ \mathbf{E}_E, \mathrm{e}_P, \omega, T, Grad_\nu T, \vec{N}_\nu, \vec{Q}_\nu, A \right\} \tag{10}$$

named *temperature-deformation configuration point*, where T - absolute temperature, $Grad_\nu T = \Delta_E{}^T \, grad T$ - its (ν_t^d)-defined gradient, A - a scalar dislocation density defined as length of dislocation lines in a representative volume element of (ν_t^d) divided by it, $\vec{Q}_\nu = J_E \Delta_E{}^{-1} \vec{q}$ and $\vec{N}_\nu = J_E \Delta_E{}^{-1} \vec{\nu}$ - are (ν_t^d) - defined heat and neutron flux vectors (with $J_E = det \Delta_E$). A seemingly small but very important difference with respect to Γ in [9] is that here e_P is taken instead of Δ_p[4]

To the above configuration point Γ there corresponds reaction point given by the set (strictly related to (ν_t^d)):

$$\Sigma_1 = \left\{ \mathbf{S}_\nu, u, s, \vec{\Phi} \right\} \tag{11}$$

where $\mathbf{S}_\nu = J_E \Delta_E{}^{-1} T \Delta_E{}^{-T}$ is the Piola-Kirchhoff stress tensor of second kind, u - the internal energy density, s - the entropy density and $\vec{\Phi} = J_E \Delta_E{}^{-1} \vec{\phi}$ - the entropy flux vector. In this way constitutive equations are simply stated as the bijection:

$$\mathcal{R} : \mathcal{S}_\Gamma \rightarrow \mathcal{S}_{\Sigma_1} \quad or \quad \Sigma_1 = \hat{\Sigma}_1(\Gamma) \tag{12}$$

with $\Gamma \in \mathcal{S}_\Gamma$ and $\Sigma_1 \in \mathcal{S}_{\Sigma_1}$. Also, an additional but very important constitutive equation which delimits elastic from inelastic behaviour is introduced by the following *dynamic yield function*

$$f = h(\mathbf{S}_\nu, T, \mathrm{e}_P, A, \vec{N}_\nu) = \hat{f}(\Gamma) \tag{13}$$

[4] This is simpler, only e_P is observable during experiments and justification comes from the fact that only six components of Δ_p are independent as discussed in previous footnote.

and the corresponding *static yield function*

$$f_o = h(\mathbf{S}^o, T, \mathbf{e}_P, A, \vec{N}_\nu) = \hat{f}(\Gamma^\#)$$

with $\mathbf{S}^o \equiv \mathbf{S}_\nu|_{\dot{p}=0}$ being *static stress* chosen to have the same direction as $\mathbf{S}$ and $\Delta\mathbf{S} \equiv \mathbf{S}_\nu - \mathbf{S}^o$ is called *overstress tensor*. Here $\dot{p} \equiv \|\mathbf{D}_p\|$ and the above functions allow the following classification:

- $f > 0, f_o = 0, \dot{p} > 0$ – viscoplastic behaviour,
- $f = f_o = 0, \dot{p} = 0$ – elastoplastic boundary and
- $f = f_o < 0, \dot{p} = 0$ – elastic behaviour.

The evolution of the considered process is described by the following *evolution equations*

$$\overset{\nabla}{\vec{Q}}_\nu = \vec{Q}^\#(\Gamma) \tag{14}$$

$$\overset{\nabla}{\vec{N}}_\nu = \vec{N}^\#(\Gamma) \tag{15}$$

$$\mathbf{D}_P = \mathbf{D}^\#(\Gamma) \tag{16}$$

$$\dot{A} = A^\#(\Gamma) \tag{17}$$

$$\dot{\omega} = \omega^\#(\Gamma) \tag{18}$$

as well as by the balance laws. The evolution functions might be also collected into the following set $\Sigma_2 = \left\{\vec{Q}^\#, \vec{N}^\#, \mathbf{D}^\#, A^\#, \omega^\#\right\}$. Due to the representation defined with regard to (ν_t^d) – configuration instead of corotational time derivatives, the above evolution equations contain much simpler material time derivatives.[5]

The above set of constitutive and evolution equations is too general for practical use. However, they must obey the second law of thermodynamics in which there appear time rates and spatial gradients of the constitutive variables. These rates and gradients are not independent but connected by the balance laws and by the kinematical constraint $< f > \dot{f}_o = 0$ (with $< x >= 1$ for $x > 0$ and $< x >= 0$ otherwise) which is a consequence of properties of above defined dynamic as well as static yield function. Multiplying these constraint equations by Lagrange multipliers and introducing them into thus extended second law we acquire independent rates and gradients (except $Grad_\nu T$ which is already included into (10)). This is the essence of Liu's theorem [12]. Therefore the extended dissipation inequality is split into the following constitutive restrictions:

$$\vec{\Phi}_\nu = \frac{1}{T}\vec{Q}_\nu \tag{19}$$

$$\mathbf{S}_\nu = \rho_\nu \partial_{\mathbf{E}_E}\Psi + < f > \Lambda^f \partial_{\mathbf{E}_E} f_o \tag{20}$$

$$s = -\rho_\nu \partial_T \Psi - < f > \Lambda^f \partial_T f_o \tag{21}$$

$$\vec{0} = \rho_\nu \partial_{Grad_\nu T}\Psi + < f > \Lambda^f \partial_{Grad_\nu T} f_o \tag{22}$$

[5] A transformation of constitutive equations and evolution equations to forms related to (ψ_t) would require the corresponding corotational derivatives.

and the following residual dissipation inequality:

$$\vec{\Lambda}^q \cdot \vec{Q}^{\#} + \vec{\Lambda}^\nu \cdot \vec{N}^{\#} + \Lambda^A A^{\#} + \Lambda^\omega \omega^{\#} + \Lambda^p : \mathbf{D}^{\#} - \frac{1}{T^2}\vec{Q}_\nu \cdot Grad_\nu T \geq 0, \tag{23}$$

where ρ_ν is the mass density in (ν_t^d) – configuration, $\Psi \equiv u - Ts$ is the free energy density and the afore mentioned Lagrange multipliers are determined as follows

$$\Lambda^\omega = -\rho_\nu \partial_\omega \Psi - < f > \Lambda^f \partial_\omega f_o \tag{24}$$

$$\Lambda^A = -\rho_\nu \partial_A \Psi - < f > \Lambda^f \partial_A f_o \tag{25}$$

$$\vec{\Lambda}^q = -\rho_\nu \partial_{\vec{Q}_\nu} \Psi - < f > \Lambda^f \partial_{\vec{Q}_\nu} f_o \tag{26}$$

$$\vec{\Lambda}^\nu = -\rho_n u \partial_{\vec{N}_\nu} \Psi - < f > \Lambda^f \partial_{\vec{N}_\nu} f_o \tag{27}$$

$$\Lambda^p = -\rho_\nu \partial_{\mathbf{e}_P} \Psi + < f > \Lambda^f \partial_{\mathbf{e}} f_o - \mathbf{S}_\nu. \tag{28}$$

The whole procedure of the explained thermodynamic analysis (standard for the extended thermodynamics) is presented in detail in [9].

3. Small Thermoelastic Strains of Isotropic Materials

In order to make the theory more explicit the next assumptions are made:[6]
(A1) all time rates, thermoelastic strain, temperature gradient, heat flux and neutron flux are small but plastic strain and damage are finite and
(A2) stress vanishes when purely elastic strain equals to zero,
which are realistic for reactor steel behaviour. Due to (A1) – assumption the thermoelastic strain may be split into purely elastic strain and thermal strain in the simplified way:

$$\mathbf{E}_E = \mathbf{E}_e + \gamma\theta\mathbf{1},$$

where $T_o\theta \equiv T - T_o$ and γ is the thermal expansion coefficient. Under such assumptions the stress is represented by the generalized Hooke's law (cf. also [1], [9], [10])

$$\begin{aligned}\mathbf{S}_\nu =& \mathcal{M} : [\mathbf{E}_E - \gamma\theta\mathbf{1}] = \\ & c_1 i_1 \mathbf{1} + 2c_2 \mathbf{E}_E + c_3 i_3 \mathbf{e}_P + c_5 i_5 \mathbf{e}_P^2 + c_4 (\mathbf{E}_E \mathbf{e}_P + \mathbf{e}_P \mathbf{E}_E) + \\ & c_6 (\mathbf{E}_E \mathbf{e}_P^2 + \mathbf{e}_P^2 \mathbf{E}_E) - (3c_1 + 2c_2)\gamma\theta\mathbf{1} - (c_3\pi_1 + 2c_4)\gamma\theta\mathbf{e}_P - \\ & (c_5\pi_2 + 2c_6)\gamma\theta\mathbf{e}_P^2,\end{aligned} \tag{29}$$

where the above listed invariants are listed below

$$i_1 = \mathbf{1} : \mathbf{E}_E, \quad i_3 = \mathbf{e}_P : \mathbf{E}_E, \quad i_5 = \mathbf{e}_P^2 : \mathbf{E}_E,$$
$$p_1 = \mathbf{1} : \mathbf{e}_P, \quad p_2 = \mathbf{1} : \mathbf{e}_P^2, \quad p_3 = \mathbf{1} : \mathbf{e}_P^3$$

[6] Larger plastic stretching may be included into this framework but this requires introduction of logarithmic plastic stretching tensor via its principal directions. Such an extension is far from trivial and will be the subject of subsequent research in this field.

and $\mathcal{M}$ is the fourth rank *tensor of elastic "constants"* [9]. In the above constitutive equation for stress all the coefficients i.e. $c_1, \ldots, c_6$ are functions of

$$\gamma_\pi \equiv \{p_1, p_2, p_3, \theta, \omega, A\}.$$

As the next step, by means of tensor representation procedures (cf. [13, 14]) evolution equations (11) and (12) with the assumption that the heat relaxation time is negligible (cf. [9]) are simplified into

$$\vec{0} = \vec{Q}_\nu + \left[k_o \mathbf{1} + k_1 \mathbf{e}_P + k_2 \mathbf{e}_P^2\right] \cdot Grad_\nu \theta - \left[k_3 \mathbf{1} + k_4 \mathbf{e}_P + k_5 \mathbf{e}_P^2\right] \cdot \vec{N}_\nu, \tag{30}$$

$$\tau_\nu \dot{\vec{N}}_\nu = \left[-\mathbf{1} + n_1 \mathbf{e}_P + n_2 \mathbf{e}_P^2\right] \cdot \vec{N}_\nu + \left[n_3 \mathbf{1} + n_4 \mathbf{e}_P + n_5 \mathbf{e}_P^2\right] \cdot Grad_\nu \theta + \left[n_6 \mathbf{1} + n_7 \mathbf{e}_P + n_8 \mathbf{e}_P^2\right] \cdot \vec{Q}_\nu, \tag{31}$$

where τ_ν is the neutron relaxation time and the heat relaxation time is neglected ($\tau_q \approx 0$ on the left hand side of (30) i.e. $\tau_q \dot{\vec{Q}}_\nu = \ldots$) which is good assumption unless extremely low temperatures are considered. The equation (30) generalizes Fourier law: taking into account thermal anisotropy induced by plastic strain (for k_1, k_2 different from zero) and heating by neutron irradiation (by means of coefficients k_3, k_4 and k_5). Its important feature shows thermal anisotropy induced by plastic strain unless $k_1, \ldots, k_6$ are all equal to zero. Indeed, magnitudes $\frac{k_1}{k_o}, \ldots, \frac{k_5}{k_o}$ should be quantified by some new experiments in order to judge whether such an anisotropy is really important for applications.

The evolution equation for plastic strain rate expressed by nonpolynomial tensor function of stress and plastic strain reads

$$\mathbf{D}_P = < f > \left[d_1 \mathbf{1} + d_2 \mathbf{S}_\nu + d_3 \mathbf{S}_\nu^2 + d_4 \mathbf{e}_P + d_5 \mathbf{e}_P^2 + d_6 \left(\mathbf{e}_P \mathbf{S}_\nu + \mathbf{S}_\nu \mathbf{e}_P\right) + d_7 \left(\mathbf{e}_P^2 \mathbf{S}_\nu + \mathbf{S}_\nu \mathbf{e}_P^2\right) + d_8 \left(\mathbf{e}_P \mathbf{S}_\nu^2 + \mathbf{S}_\nu^2 \mathbf{e}_P\right)\right] \tag{32$_1$}$$

whereas the corresponding damage rate is given by

$$\dot{\omega} = < f > \left[3d_1 + d_2 \mathrm{tr}\mathbf{S}_\nu + d_3 \mathrm{tr}\{\mathbf{S}_\nu^2\} + d_4 p_1 + d_5 p_2 + 2d_6 \mathrm{tr}\{\mathbf{S}_\nu \mathbf{e}_p\} + 2d_7 \mathrm{tr}\{\mathbf{S}_\nu \mathbf{e}_p^2\} + 2d_8 \mathrm{tr}\{\mathbf{S}_\nu^2 \mathbf{e}_p\}\right](1 + \omega). \tag{32$_2$}$$

Again, the scalar coefficients $k_o, \ldots, k_5$, $n_o, \ldots, n_8$, τ_ν, $d_1, \ldots, d_8$ depend on the elements of the set γ_p.

The above flow rule is non–associate i.e. plastic strain rate is not necessarily perpendicular to the yield surface. Indeed, such a normality does not follow from plastic work extremum (c.f. [21]). This has been confirmed by multiaxial experiments (cf. [15, 16]) at small strains and small as well as medium strain rates. In [15] for such a case scalar material coefficients d_2 and d_3 being dominant were calibrated as functions of plastic strain magnitude and direction showing strong directionality effect as well as impossibility of constructing a *"universal"* equivalent plastic strain – equivalent stress curve as essential ingredient of an associate flow rule. Moreover, the corresponding calibration in the more general

case of finite plastic strains has recently been performed finding $d_2, \ldots, d_8$ (c.f. [22]) including comparison with the most general normality rule derived by Rice in his papers (c.f. for instance [23]). It has been shown that non-associativity is closer to the data from multiaxial experiments.

Finally, let us consider the simplest case when

(A3) plastic strain itself is small of the same order as elastic strain.

Then the free energy may be approximated by a bilinear function (cf. also [9]):

$$\rho_o \Psi \approx \rho_o \Psi_1(\mathbf{E}_e, \theta) + l_1 \vec{Q}_\nu \cdot \vec{Q}_\nu + l_2 \vec{N}_\nu \cdot \vec{N}_\nu + l_3 \vec{Q}_\nu \cdot \vec{N}_\nu, \tag{33}$$

where l_1, l_2 and l_3 are constants. This means that k_1, k_2, k_4, k_5, n_1, n_2, n_4, k_5, n_7, k_8 are negligible in (30) and (31). Now, small deviations from thermodynamic equilibrium permit Onsager – Casimir reciprocity relations. Thus from the residual dissipation inequality there follow kinetic relations which restrict the coefficient k_3 to be

$$k_3 = -2\frac{l_3}{l_1}$$

while n_3 and n_6 may be arbitrary. Since a thermal effect on neutron flux is not observed experimentally (being small of higher order) it is reasonable to neglect terms with $Grad_\nu \theta$ and $\vec{Q}_\nu$ in (31) (i.e. $n_3 \approx 0$ and $n_6 \approx 0$). For such a fully linear case this would have as a consequence the next known mostly simplified evolution equation for neutron flux:

$$\tau_\nu \dot{\vec{N}}_\nu + \vec{N}_\nu = \vec{0}.$$

4. Concluding Remarks

The results presented in this paper are briefly summarized as follows:

- The theory is convenient for calibration by experiments and accounts for quite general interaction between neutron irradiation creep, thermomechanical damage and viscoplasticity.
- For its application it would be necessary to perform multiaxial viscoplastic experiments during as well as after irradiation in order to calibrate the material constants. These experiments must be escorted by careful measurement of interacting effects.
- The flow rule is non-associate. It permits an easy explanation of mechanical as well as thermal anisotropy induced by plastic strain explicitly for the practically important case of small elastic but finite damage–plastic strain.

Acknowledgement. Discussions with Drs C. Albertini and M. Montagnani of JRC CEC – Ispra as well as Dr D. Nikezić of Kragujevac University on the subject are highly appreciated.

REFERENCES

[1] Mićunović, M.: *On low strain-rate viscoplasticity of continuously damaged materials.* In: Current advances in mechanical design and production IV, Kabil, Y. H.; Said, M. E. (eds.) 181–188. Oxford: Pergamon Press 1989

[2] Kröner, E.: *Allgemeine Kontinuumstheorie der Versetzungen und Eigenspannungen* Arch. Rational Mech. Anal. 4 (1970) 273–334.

[3] Stojanović, R.: *Reference-state problem in non-linear elasticity theory.* Physica Status Solidi **2** (1962) 566–575.

[4] Bilby, B. A.: *Continuous distributions of dislocations.* Progress in Sol. Mech. **1** (1960) 329–398.

[5] Mićunović, M.: *A geometrical treatment of thermoelasticity of simple inhomogeneous bodies : I- Geometric and kinematic relations.* Bull. Acad. Polon. Sci., Ser. Sci. Techn. **22** (1974) 663–642.

[6] Dashner, P. A.: *Invariance considerations in large strain elastoplasticity.* J. Appl. Mech. **53** (1986) 55–60.

[7] Murakami, S.: *Mechanical modelling of material damage.* ASME J. Appl. Mech. **55** (1988) 280–286.

[8] Murakami, S.; Sanomura, Y.: *Creep and creep damage of copper under multiaxial state of stress.* In: Plasticity today, Sawczuk A.; Bianchi, G. (eds.) London: Elsevier 1985.

[9] Maruszewski, B.; Mićunović, M.: *On Neutron Irradiation of an Isotropic Thermoplastic Body* Int. J. Engng. Sci. **27/8** (1989) 955–965.

[10] Mićunović, M.: *A Thermodynamic Model of Ideal Cyclic Viscoplasticity* In: Transactions of SMIRT-9, Vol. L., Wittmann, F. H. (ed.) 195–203. Rotterdam: Balkema 1987.

[11] Mroz, Z.; Shrivastava, H. R.; Dubey, R. N.: *A Non-Linear Hardening Model and Its Application to Cyclic Loading.* Acta Mechanica **17** (1973) 277–290.

[12] Müller, I.: *The Coldness, a Universal Function in Thermoelastic Bodies.* Arch. Rational Mech. Anal. **41** (1971) 319–332.

[13] Truesdell, C.; Noll, W.: *The Non-Linear Field Theories of Mechanics.* In: Handbuch der Physik III/3, Fluegge S. (ed.) Berlin: Springer 1965.

[14] Spencer, A. J. M.: *Theory of invariants.* In: Continuum Physics, Eringen A. C. (ed.) New York: Academic Press 1971.

[15] Albertini, C.; Montagnani, M.; Mićunović, M.: *Viscoplastic Behaviour of AISI 316 H - Multiaxial Experimental Results.* Transactions of SMIRT-10, Los Angeles 1989.

[16] Albertini, C.; Montagnani, M.; Mićunović, M.: *Viscoplastic behaviour of aisi 316h - multiaxial experimental results and preliminary numerical analysis*, Nuclear Engineering and Design, Vol. 130, p. 1, 1991.

[17] Mićunović, M.: *Inelastic memory versus viscoplasticity of continuously damaged materials.* Journal of the Mechanical Behaviour of Materials, Vol. 4, No. 4, pp. 331–341.

[18] Mićunović, M.: *A viscoplasticity theory of irradiated materials*, 4th IUTAM symposium: Creep in Structures, held in Krakow 1990, p. 139, (ed. M. Zyckowski) Springer 1991.

[19] Mandel, M.: *Sur la definition de la vitesse de déformation élastique et sa relation avec la vitesse de constrainte*, Int. J. Solids Structures, Vol. 17., pp. 873–878. 1981.

[20] Lubarda, V.; Lee E. H.: (1981): *A correct definition of elastic and plastic deformation and its computational significance*, ASME J. Appl. Mech., Vol. 48., pp. 35–40.

[21] Mićunović, M.: *Normality rule from plastic work extremals?*, Materials Science Forum (Trans Tech Publ.), Vol. 123–125, pp. 609–616., 1993

[22] Mićunović, M.: *A comparison of some viscoplasticity models from multiaxial experiments at large strains*, Proceedings of XX Yugoslav congress of mechanics, Kragujevac 1993.

[23] Rice, J. R.: *Inelastic constitutive relations for solids: an internal variable theory and its application to metal plasticity*, J. Mech. Phys. Solids, Vol. 19., pp. 433–455. 1971

О ВЯЗКОПЛАСТИЧНОСТИ ОБЛУЧЕННОЙ СТАЛИ

Для принятия в расчет повреждений, вызванных облучением, необходимо примененить теорию вязкопластичности материала с дефектами. Одна из таких теорий представлена в данной работе. Ее специфичность

- принятие в расчет общего взаимодействия процесса облучения, и вязкопластичности. Эволюционные уравнения для скорости пластичной деформации, теплового и нейтронного струения включают в себя материальные функции, зависящие от пластичной деформации и температуры. Специальный случай конечной пластичной, но малой термоупругой деформации, характерный для стали, вводит значительное упрощение теории, которое позволяет калибрацию теории на основе вышеосных динамических экспериментов. Анализируется также и совсем специальный случай малых пластичных деформаций.

O VISKOPLASTIČNOSTI OZRAČENIH ČELIKA

Za uzimanje u obzir oštećenja uzrokovanog ozračenjem neophodna je jedinstvena teorija viskoplastičnosti oštećenih materijala. Jedna od takvih teorija je u ovom radu prikazana. Njena specifičnost je uzimanje u obzir opšteg međudejstva ozračenja i viskoplastičnosti. Evolucione jednačine za brzinu plastične deformacije, toplotni i neutronski fluks uključuju materijalne funkcije zavisne od plastične deforma 'je i temperature. Posebni slučaj konačne plastične a male termoelastične deformacije karakterističan za čelike omogućava značajno uprošćenje teorije koje omogućava kalibraciju teorije na osnovu višeosnih dinamičkih eksperimenata. Sasvim poseban slučaj malih plastičnih deformacija se takođe analizira.

Milan V. Mićunović
Mašinski fakultet,
Sestre Janjića 6
YU-34000 Kragujevac, Yugoslavija