TRANSFORMATION PLASTICITY
THE MECHANISM, CONSTITUTIVE EQUATION AND APPLICATIONS

T. Inoue

Department of Mechanical Systems Engineering, Fukuyama, Japan

1. Introduction

The transformation plasticity is known to contribute a drastic effect on the simulation of some practical engineering courses of thermo-mechanical processes, such as heat treatment, welding, casting and so on involving phase transformation of steels. Most constitutive laws for transformation plasticity have been treated to be independent of ordinal thermo-plasticity. Considering that the mechanisms for both strains are essentially with no difference from metallurgical viewpoint, the constitutive equation for transformation plastic strain rate is expected to be described in relation with plasticity theory.

A phenomenological mechanism of transformation plasticity is discussed, in the first part of the paper, why the transformation plastic deformation takes place under a stress level even lower than the characteristic yield stress of mother phase: This is principally based on the difference in thermal expansion coefficient of mother and new phases. Bearing in mind that it is also a kind of plastic strain, a unified plastic flow theory is derived by introducing the effect of progressing new phase into the yield function of stress, temperature and plasticity related parameters. Thus obtained strain rate reveals to include the transformation plastic part in addition to mechanical and thermal plastic components.

Application of the theory is carried out to simulate some complicated cases of varying stress and temperature, and the results are compared with experimental data.

2. A phenomenological model

Consider that the material is composed of mother and new phases, say austenite and pearlite, or martensite, being connected parallely each other [1]. Since the thermal expansion coefficient of *mother phase* α_m is larger than that of *new phase* α_n in most case, tensile thermal stress is essentially induced in the mother phase. External stress in addition to the tensile thermal and phase transformation stresses brings out to large value sometimes beyond the yield stress, which is the initiation of plastic deformation, or transformation plasticity. Simple numerical calculation will be illustrated how the stresses in mother and new phases vary during phase transformation, and the dependence of applied stress is discussed.

3. Unified transformation and thermoplasticity constitutive equation

In order to formulate a constitutive equation of a body under phase transformation, we assume that the material point focused is composed of N kinds of phases, which include all phases with the volume fraction ξ_I $(I = 1, 2, 3, ..., N)$ and that the mechanical and thermophysical property χ is represented by the *mixture law* such that $\chi = \sum_{I=1}^{N} \xi_I \chi_I$, with $\sum_{I=1}^{N} \xi_I = 1$. Stress state related to the yielding of the I-th phase (say, mother phase, or austenite) is assumed to be affected by other phases (new phase, or pearlite) with the volume fraction ζ_J $(J = 1, 2, 3, ..., M)$ [2]. Then, the plastic state of the I-th phase is controlled by the yield function in the form,

$$F_I = F_I(\sigma_{ij}, T, \varepsilon^p_{Iij}, \kappa_I, \zeta_J), \qquad (I = 1, 2, ..., N \;;\; J = 1, 2, ..., M) \quad . \tag{1}$$

Here, σ_{ij}, T and κ_I are respectively stand for uniform stress, temperature and plastic hardening parameter.

Applying the normality rule for the plastic strain rate, we finally have

$$\dot{\varepsilon}^{p}_{Iij} = \Lambda_I \frac{\partial F_I}{\partial \sigma_{ij}} = \hat{G}_I [\left(\frac{\partial F_I}{\partial \sigma_{kl}} \dot{\sigma}_{kl} + \frac{\partial F_I}{\partial T} \dot{T} \right) + \sum_{N=1}^{\tilde{N}} \frac{\partial F_I}{\partial \zeta_J} \dot{\zeta}_J] \frac{\partial F_I}{\partial \sigma_{ij}} \quad , \tag{2}$$

in which the first tem is the ordinal thermo-mechanical strain rate while the second corresponds to the TP strain rate. The TP strain rate possibly reveals to so-called Greenwood-Johnson type formula [3] in the special case of two phase.

$$\dot{\varepsilon}^{tp} = 3K\left(1-\xi\right)\dot{\xi}\sigma \, . \tag{3}$$

4. Application to the strain response for stress-temperature variation

The theory developed is now applied to some cases under varying stress and temperature [4]. Total strain in such cases of varying temperature reads

$$\varepsilon\left(T\right) = \varepsilon^{e} + \varepsilon^{th} + \varepsilon^{m} + \varepsilon^{tp} = \frac{\sigma}{E} + \int_{T_s}^{T} \left\{ \left[\alpha_m \left(1-\xi\right) + \alpha_n \xi \right] + \beta \frac{\partial \xi}{\partial T} \right\} \mathrm{d}T + 3\int_0^{\xi(T)} K\left(1-\xi\right)\sigma \mathrm{d}\xi \, . \tag{4}$$

The first case example of application is to draw so-called temperature-elongation diagram depending on applied stress, and the second is related to fire distinguishment of structure made of a fire resistant steel (FR490A) heated and cooled between room temperature and 900℃ with decreasing and increasing stress. The results of simulation are compared with some experimental data to verify the theory developed.

5. Summary

A discussion on the mechanism from thermo-mechanical viewpoint is carried out, and the constitutive law is derived for unified thermomechanical-transformation plasticity theory. Application of the theory is made to some processes under varying temperature and stress.

Acknowledgement The author is indebted to express his gratitude to IMS-Japan, NEDO and METI for their financial supports to this project. Thanks are also due to my student, T. Tanaka, K. Sato, A. Nishimura and E. Wakamatsu, Fukuyama University, for their cooperation with experiments.

REFERENCES

[1] T. Inoue(2007), *Unified transformation-thermoplasticity and the Application* (in Japanese), J. Soc. Materials Science, Japan, 56 p. 354-359.

[2] T. Inoue(2008), On Phenomenological Mechanism of Transformation Plasticity and Inelastic Behavior of a Steel subjected to Varying Temperature and Stress --- Application of Unified transformation- thermoplasticity Theory (in Japanese), J. Soc. Materials Science, Japan, 57 pp.225-230.

[3] T. Inoue(2007), A Phenomenological Mechanism of Transformation Plasticity and the Unified Constitutive Equation of Transformation- thermo-mechanical Plasticity, Proc. APCOM'07 Kyoto, JAPAN CD published.

[4] G.W. Greenwood and R.H. Johnson (1965), *The deformation of metals under small stresses during phase transformations*, Proc. Roy. Soc., 283A p.403-422.