Complete Formulation of the Subloading Surface Model

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ABSTRACT

The original concept of the subloading surface was first advocated in 1977 (Hashiguchi and Ueno, 1977) in order to describe the plastic strain rate induced by the rate of stress inside the yield surface so that the smooth elastic-plastic transition is described. Then, the formulation of the subloading surface model for the elastoplastic deformation has been highly developed from the past ones (Hashiguchi, 1980, 1989). Further, it has been applied to the descriptions of wide classes of irreversible mechanical phenomena, i.e. the monotonic and cyclic loading of metals (Hashiguchi, 1989; Hashiguchi and Protasov, 2004; Hashiguchi and Yoshimaru, 1995; Hashiguchi et al.; 2012) and soils (Hashiguchi and Ueno, 1977; Hashiguchi and Chen, 1998; Hashiguchi et al., 2002; Hashiguchi and Mase, 2007; Hashiguchi and Tsutsumi, 2001, 2003, 2006; Wongsaroj et al., 2007; Yamakawa et al., 2010), the viscoplastic deformation behavior (Hashiguchi et al., 2005), the damage behavior (Hashiguchi and Oka, 2014), the phase transformation behavior (Hashiguchi and Okamura, 2014), the friction behavior (Hashiguchi et al., 2005; Hashiguchi and Ozaki, 2008) and the crystal plasticity (Hashiguchi, 2013a). On the other hand, the other unconventional plasticity, i.e. cyclic plasticity models, e.g. the multi surface model (Mroz, 1967), the two surface model (Dafalias and Popov, 1975; Yoshida and Uemori, 1992) and the superposed kinematic hardening model (Chaboche et al., 1979; Onho and Wang, 1993), which does not assume that the inside of yield surface is an elastic domain but assume the existence of the purely-elastic domain, have been formulated only for the description of cyclic loading behavior of metals. They would be inapplicable to the descriptions of the damage behavior, the friction behavior, the crystal plasticity, the deformation behavior of plastically pressure-dependent granular materials, e.g. soils, the finite deformation behavior, etc. Their limitations would be caused by the assumption of the existence of the purely elastic domain and the assumption of the kinematic hardening for the development of plastic deformation which would be substantially independent of the kinematic hardening. The extensive applicability of the subloading surface model to wide classes of irreversible mechanical behavior is based on the distinguished advantages of the subloading surface model such that it does not require the yield judgment on whether or not the stress reaches the yield surface and it is furnished with the automatic controlling function to attract the stress to the yield surface so that the stress is pulled back automatically to the yield surface when it goes out from the yield surface in numerical calculation due to finite incremental steps. However, elaborated formulation is required for the description of the cyclic loading behavior of elastoplastic deformation. In particular, the translation rules of the anisotropic hardening variable (back-stress) and the elastic-core, i.e. similarity-center of the yield and the subloading surfaces and the description of the Masing rule, i.e. the difference of curvatures depending on initial, reloading and reverse loading curves have been modified repeatedly but they have not been formulated in the rigorous forms with clear and concise physical meanings in the past (Hashiguchi et al., 2012; Hashiguchi, 2013a, b). Now, the formulation is completed passing near a half century after the concept of the subloading surface was proposed in 1977.

The novel physical interpretation is given first for the subloading surface concept in this article. Then, the complete formulation of the subloading surface model for the elastoplastic deformation is presented in the framework of the hypoelastic-based plasticity. It is described in the concise mathematical form with clear physical meanings. In particular, the translation rules of the anisotropic hardening variable and the elastic-core and the description of the Masing rule are formulated rigorously. It possesses the distinguished ability in both aspects of the description of material behavior and of the numerical analysis of boundary-value problems. Further, it is furnished with the basic structure which is compatible to the description of the finite elastoplastic deformation as the extension to the multiplicative hyperelastic-based plasticity will be shown in the latter half of this article. On the other hand, the extension of the other unconventional models to the multiplicative hyperelastic-based plasticity has not been shown so far and it would be impossible. Eventually, it will be concluded that the subloading surface model possesses the distinguished ability to describe wide classes of irreversible mechanical phenomena for various materials ranging from the macro to micro levels up to the finite deformation.