Finite Element study of metal-based additive manufacturing with an account of phase transformation

M. H. Yoon[1] and Y. S. Han[2*]

[1]Department of Mechanical Engineering, Kumoh National Institute of Technology, Gumi, Gyeongbuk, S. Korea
[2]Department of Mechatronics Engineering, Incheon National University, Incheon, S. Korea

[*]Corresponding author: yshan@inu.ac.kr

1. Introduction

An analysis of additive manufacturing poses several challenges as it involves complex material phenomena which result from the interaction of thermal, mechanical, and metallurgical behaviors. For example, phase transformation is governed by the temperature history. Conversely, during a phase transformation, the latent heat influences the actual temperature field. Thermal loading applied to a structure induces deformation. In addition, each phase transformation is a source of deformation, mainly due to density variations and the degree of transformation plasticity.

The present study focuses on obtaining a systematic finite element implementation of the constitutive equation considering phase transformation and transformation plasticity. Borrowing the key idea in the hypoelastic formulation based upon additive decomposition, an efficient implementation of the stress-update procedure is proposed, and a calculation of tangent moduli accounting for the constitutive equation that includes transformation plasticity is formulated. The hypoelastic formulation is often employed in finite element analyses with small elastic strain mainly due to its conceptual simplicity. It is accurate enough to represent Hooke's law up to the leading order as long as the elastic strains remain small. In addition, the influence of the phase transformation and the transformation plasticity on the residual stress has been investigated using the metallurgical parameters in phase evolution equation adjusted with respect to various cooling curves in a CCT-diagram.

2. Formulation of thermo-metallurgical and mechanical analyses

The kinetic equation of metallurgical transformation proposed by Leblond and Devaux [1] is applied to calculate the phase volume fraction. In this work, it is assumed it is assumed that up to four different phases can be present in the material, which represent ferrite-pearlite, bainite, martensite, and austenite. The detailed information on the phase evolution equation and its implementation to FE constitutive model is available on the reference [2, 3, 4].

The energy equation with an account of phase transformation has been implemented to the constitutive model. In addition, phase volume fractions of each phase are taken into account for thermal material properties such as the specific heat, the enthalpy, and thermal conductivity for thermal analysis.

The thermo-elastoplastic constitutive equations including phase transformation and transformation proposed by Leblond et al. [3] have been employed for mechanical analysis. A mixture of phases in steel is divided into two categories: the weak phase phase and the hard phase. Thermal strain and the yield strength of the phase mixture has been calculated with a law of mixture rule. The Leblond's model distinguishes between two regimes according to whether the macroscopic equivalent stress does or does not reach the yield stress of the phase mixture. Therefore, two different plastic flow rules are prescribed separately: transformation plasticity and macroscopic plasticity.

In this study, small elastic strains, compared with the plastic strains, are assumed. Thus, the hypoelastic formulation can adequately describe the realistic elastic material responses. In addition, only an isotropic material is considered, and the J2 flow model based on the von Mises yield surface is applied. It is also assumed that the elastic properties apart from the thermal expansion coefficients remain invariant with respect to the phase transformation. This leads to efficiency and simplicity. As discussed above, for thermal expansion coefficients, the mixture rule is applied to take into account the phase transformation. This enables us to treat a mixture of the weak and hard phases as an equivalent single homogeneous phase. Constitutive equations within the framework of thermoelastoplasticity are used under the additive decomposition of the rate of deformations in conjunction with the hypoelastic formulation. In the hypoelastic formulation, the trial stress is to be defined, and a rotation neutralization procedure is required to satisfy material objectivity.

The heat during electron beam deposition is applied as a volumetric heat source with the double ellipsoidal model proposed by Goldak et al. [5].

Acknowledgment

References

[1] Leblond, J. B., and Devaux, J. C., 1984, “A New Kinetic Model for Anisothermal Metallurgical Transformations in Steels Including Effect of Austenite Grain Size,” Acta Metall., 32_1_, pp. 137–146.

[2] Leblond, J. B., and Devaux, J. C., 1989, “Mathematical Modeling of Transformation Plasticity in Steels I: Case of Ideal-Plastic Phase,” Int. J. Plast., 5, pp.551–572.

[3] S. Kalpakjian and S. R. Schmid, *Manufacturing Processes for Engineering Materials*, Second Ed. Addison-Wesley Publishing Company, New York, USA, (1992).

[4] Koistinen, D. P., and Marburger, R. E., 1959, “A General Equation Prescribing the Extent of the Austenite-Martensite Transformation in Pure Iron-Carbon Alloys and Plain Carbon Steels,” Acta Metall., 7, pp. 59–60.

[5] Goldak, J., Chakravarti, A., and Bibby, M., 1984, “A New Finite Element Model for Welding Heat Sources,” Metall. Trans. B, 15, pp. 299–305.