Extension and Application of Hot Workability Prediction Model in Thermomechanical Processing

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Predicting hot workability is a critical challenge in thermomechanical processing. Traditional approaches are primarily based on the theory of hot processing maps, which evaluate power dissipation efficiency and deformation instability factor under various deformation conditions. The power dissipation efficiency characterizes the kinetics of microstructural evolution, whereas the deformation instability factor reflects the stability of plastic flow. Although the hot processing map theory has been widely applied to the hot deformation of various materials across a broad range of forming conditions, existing methods still exhibit limitations that hinder their practical application or lead to prediction inaccuracies. In this study, a data-driven model is developed based on the hot processing map theory to predict hot workability. Specifically, the conventional direct relationship between deformation conditions and hot workability is extended to a multidimensional space that incorporates deformation conditions, microstructural states, and hot workability. Based on the SHAP analysis, the relationships among these three factors are further quantitatively characterized. The influences of deformation conditions and microstructural states on hot workability under various processing conditions are systematically elucidated. To demonstrate the general applicability of the proposed approach, 316L austenitic stainless steel, low-carbon alloy steel, and nickel-based alloys are investigated. Furthermore, experiments involving dynamically varying deformation conditions and double-pass hot deformation are conducted to validate the method's capability in handling complex thermomechanical processes. The proposed model demonstrates strong potential for application in complex thermomechanical processing and provides a powerful tool for the design and optimization of processing routes. Future work will focus on extending the model to more complex material systems, such as duplex stainless steels and titanium alloys.

KEYWORDS: HOT DEFORMATION – HOT WORKABILITY – RECRYSTALLIZATION – ARTIFICIAL INTELIGENCE

We proposed a hot workability prediction method that can predict hot workability under dynamically changing deformation conditions and multi-pass deformation processes. Specifically, this method considers the combined effects of deformation conditions and microstructural state. First, the microstructural state is calculated in real time using an internal-state-variable constitutive model. Here, the microstructural state is represented by dislocation density and recrystallization fraction, because many studies have shown that these two parameters directly reflect hot workability. The constitutive model is then connected with two cascaded neural network models. The microstructural state and deformation conditions are used to calculate the power dissipation efficiency, which describes the proportion of plastic energy used for microstructural evolution. Then, the microstructural state, deformation conditions, and power dissipation efficiency are combined to calculate the deformation instability factor, which reflects plastic stability. Single-pass deformation data under different deformation conditions are used to train the model. The detailed model structure and training process can be found in our previous papers.

The applicability of the model has been discussed in detail in our previous paper, including single-pass deformation under constant conditions, dynamic deformation conditions, and industrial applications. Here, the model applicability is further validated using a set of double-pass hot deformation data with different inter-pass holding times.

Fig. 1 compares the predicted and experimental hot processing maps during re-deformation. Good agreement can be observed. Increasing the inter-pass holding time delays the occurrence of plastic instability at high strain rates and low deformation temperatures. At moderate strain rates, a longer inter-pass holding time is unfavorable for energy dissipation through microstructural evolution, which is attributed to the suppressed dynamic recrystallization behavior.

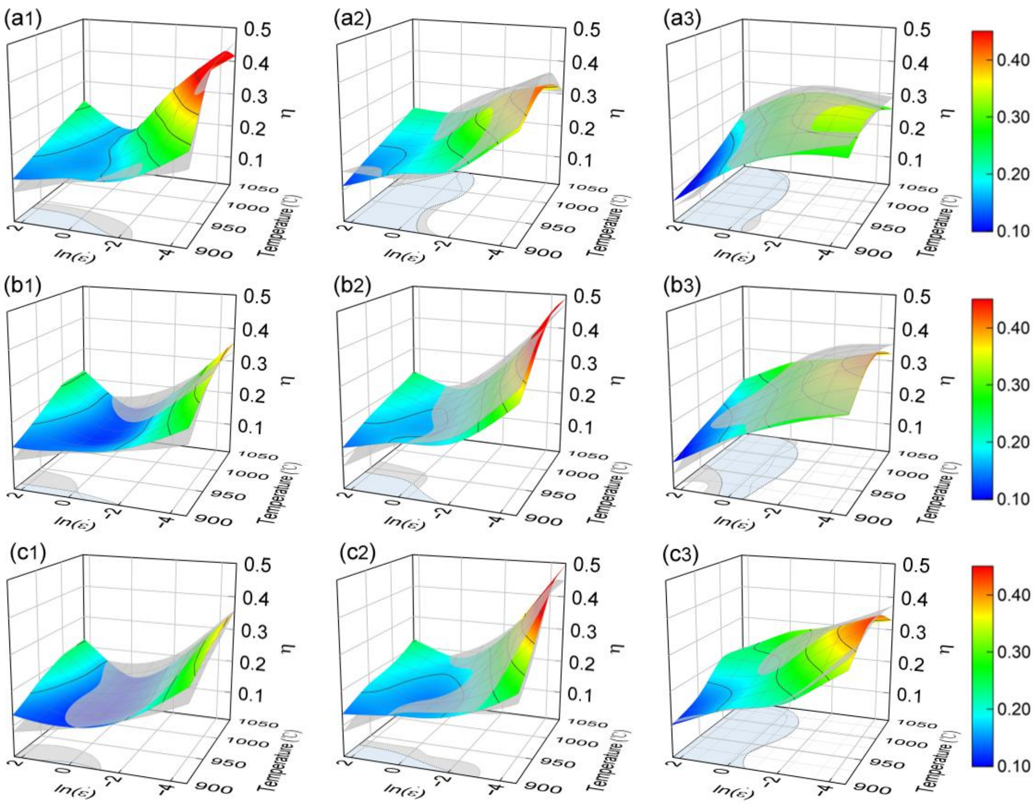

Fig.2 – The comparison of the predicted and experimental hot processing maps during re-deformation.

It is worth noting that, at low strain rates, the effect of inter-pass holding time changes significantly as re-deformation proceeds. At small re-deformation strains, increasing the inter-pass holding time reduces the power dissipation efficiency. However, at larger re-deformation strains, increasing the inter-pass holding time enhances the power dissipation efficiency. This may be related to grain growth after recrystallization saturation at low strain rates. This phenomenon will be analyzed in detail later, and the underlying mechanism will be further explained using SHAP analysis.

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