論 文 の 内 容 の 要 旨

論文題目　Quantification of microstructure evolution under hot forming for the control of mechanical properties of stainless steel
（ステンレス鋼の材質制御のための熱間加工内部組織変化の定量化）

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Hot deformation processing plays an important role in the industry for the production of steels with a desired geometry and to improve its mechanical properties. Achieving the first requires control of plastic flow, i.e. the plastic deformation, while achieving the second means to control the nature and the rate of microstructural evolution, i.e. the metallurgical phenomena.

In hot forming processes, i.e., above the recrystallization temperature, the material flow behavior is often complex. Hardening and softening mechanisms are present, and both are significantly influenced by process parameters, i.e., strain, strain-rate, forming temperature and interpass time between the forming steps. A given combination of such parameters yields a particular metallurgical phenomenon and, consequently, microstructural changes (microstructure evolution). Microstructural changes that occur during deformation are called dynamic events and the changes which are happen after deformation, i.e. during interval time between two different stages of deformation in multi-pass forming processes, are called static events. These kinetics affect the mechanical characteristics of the metal such as strength and ductility, which are often manifested in the flow curves, hence influencing the forming processes. The dependence of the flow curves on the processing parameters is usually represented through constitutive equations.

To be useful in metal-forming analyses, the flow curves of metals must be determined experimentally for the process conditions that exist in metal-forming processes. Several constitutive equations, based on experimentally measured data, have been proposed in order to establish the flow behavior on a great number of metals and alloys. Most of these relationships are either phenomenological or physically-based models. The need for greater accuracy to predict the flow curves has encouraged many researchers to develop suitable acquisition methods and constitutive models for different materials.

Uniaxial compression test is the most common method employed for data generation to study the flow behavior of materials. Generally, in the compression test, the obtained load-deformation data is converted into the engineering and/or true stress-strain data for further analysis. This is called conventional approach.

Recently, the inverse approach has been also applied to overcome the limitations of the conventional approach, such as heterogeneous deformation and non-isothermal conditions. In the inverse methodology, a finite-element model is used for the simulation of the experiment itself. The load-deformation data from the compression test is compared with the load-deformation data of a thermomechanical finite-element model in order to obtain the coefficients of a proposed flow curve. The basic principle of the method is searching for the material constants that yield the minimum error norm defined as the distance between measured and computed process parameters.

The kinetics during the dynamic and static events are driven by single- and double-compression tests, inverse analysis and regression analysis in order to obtain the parameters of the constitutive equations. These equations are one special form of material genome, term coined by Yanagimoto, as these set of equations can quantitatively describe the kinetics of microstructural evolution during hot forming. This methodology was first applied to plain carbon steels, and more recently, a systematic acquisition method to obtain the material genome was applied to tool steels.

Metals with different compositions have different hot forming behaviors. If we focus only on steels, the kinetics of microstructural evolution are strongly dependent on the amount of micro-alloying elements. In view of this complexity and the considerable number of steel compositions that are hot formed, it is not surprisingly that only a small fraction of desirable material genome is available in the literature. In order to broaden the range of applications of microstructure analyses, more consistent data for microstructure evolution, i.e. material genome, is strongly demanded.

The main goal of this work is to obtain *new material genome* with the focus on the *stainless steel*, in order to explore how the microstructure of those steels evolves during the forming processes.

This thesis is divided in 8 Chapters. Some basic definitions, motivation and objectives of the research are presented in Chapter 1. In Chapter 2, the microstructural evolution kinetics during hot forming is described. The most used approaches for calculation of flow curve are reviewed, together with the current models available in the literature for obtaining the constitutive equations of microstructural evolution during the dynamic and static events.

Chapter 3 deals with the methodology used for the acquisition of the material genome. The methodologies developed by Yanagida and Yanagimoto, and Soltanpour and Yanagimoto are fully described. It is based on single- and double-compression tests, inverse analysis and regression analysis in order to obtain the parameters of the material genome during the dynamic and static events. However, average errors of 2% on the inverse analysis are on the same order of magnitude of the variability of the experimental data obtained from the compression tests. Therefore, in order to obtain a more accurate flow curve which represents the actual behavior of the material, the errors on the analysis should be smaller than 1%. Keeping a lower error in the inverse analysis reduces the error propagation to the next steps in the analysis. Therefore, in order to obtain the parameters of the flow curve using inverse analysis with the smallest error or at a constant acceptable error (smaller than 1%), a complementary procedure to obtain the parameters of the flow curve by inverse analysis is proposed. It uses the sine-hyperbolic Arrhenius relation for validation of the flow curves and to calculate the value of the steady-state stress.

Based on the methodologies described Chapter 3, the kinetics of microstructural evolution during hot forming, i.e., the material genome, of three classes of stainless steel, i.e. the SUS316 austenitic stainless steel, the SUS420J2 martensitic stainless steel and SUS329J3L duplex (austenitic and ferritic) stainless steel are presented in Chapters 4, 5 and 6, respectively. The obtained equations are capable to reflect the transient changes in forming conditions, such as temperature and strain-rate, and can be used to optimize the final microstructure of these steels during hot forming.

In Chapter 7, the application of the material genome is assessed during rolling schedules of seamless pipes, taking the material genome of the SUS316 stainless steel as an example. The material genome is used as the boundary condition in an incremental type microstructural model to estimate the microstructure changes after the transient changes in the process parameters. The outcome of the grain size evolution is reproduced reasonably well showing that proposed methodology can be used to simulate a complex thermomechanical process akin to the rolling schedules of seamless pipes.

This study complements the earlier works from Yanagida and Yanagimoto, and Soltanpour and Yanagimoto, and provides further validation to their methodology and its capabilities in regards to:

- Materials: earlier works were focused on the plain carbon steel and tool steel, while this work concentrates on the stainless steel. This shows the ability of the methodology to obtain the material genome of different materials, and the potential for compatibility and application with other alloys and materials.
- Process conditions: between the preliminary studies and the current work, samples were formed at strain rates of 0.01-50s-1 and temperatures of 900-1150° C, expanding the range of process conditions.
- Methodology: a complementary method to obtain the parameters of the flow curve by inverse analysis is proposed. It uses the sine hyperbolic Arrhenius relation for validation and to calculate the value of the steady-state stress.
- Material behaviours: the current work presents the effects and analysis of the kinetics of strain induced precipitation during static events, which was not taken into consideration in previous studies. This was found to have significant implications on the microstructure evolution kinetics.
- Application: the application of the material genome during rolling schedules of seamless pipes is assed. The obtained results demonstrate that the proposed methodology and the material genome can be used to simulate a complex thermo-mechanical process akin to the rolling schedules of seamless pipes. In the manufacturing of seamless pipes, the old fashioned concept of producing the shape and heat treating to obtain the final structure is still dominant, and the application of thermo-mechanical controlled processing techniques in such processes is still to be developed.

The material genome is indispensable for the design and optimization of thermomechanical processes. Lacking of material genome for steels together with a general multi-scale model to connect the microstructure and mechanical properties are still the major challenges which hinder the further applications of numerical models to optimize industrial processes.