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Original Research

Microstructure-based hot extrusion process control principles for nickel-base superalloy pipes

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ABSTRACT

The properties of nickel-base superalloy pipes are determined by microstructure, and the microstructure can be tuned by hot extrusion process. There are two major questions in hot extrusion: one is how to successfully extrude pipes without apparent defects, the other is how to make the microstructure under control. However, up to now, there is no systematical report about hot extrusion process and microstructure control for nickel-base superalloys. In present study, a series of technical control principles for hot extrusion are proposed basing on practical manufacture facts, large amounts of experimental studies and finite element simulation of several typical nickel-base superalloys. The common used technical control principles can be applied for hot extrusion parameters determination to maintain safety hot extrusion and microstructure control. In the investigation of microstructure control based hot extrusion principles, the action rules of different working parameters on hot extrusion field quantities were established. The upper and lower limits of different principles were obtained in consideration of materials characteristics and extruder conditions. The limitations were overlapped on the action rules to determine the optimized hot extrusion parameters. The microstructure-based control principle proposed in present work can provide theoretical guidance for hot extrusion parameter determination and optimization.

1. Introduction

Nickel-base superalloy pipes are widely used in chemical, oil and gas industries, nuclear fields and ultra-supercritical power plants due to the excellent mechanical properties, good microstructure stability and corrosion resistance at elevated temperatures [1–3]. The rapid development of these fields has proposed an urgent need for large amount of high quality nickel-base superalloy pipes [4,5]. Generally, the outstanding properties of these alloys highly depend on microstructure which can be controlled by tuning hot deformation parameters such as temperature, strain rate and strain [3,6]. For example, the investigation for alloy 028 pipe shows that the corrosion resistance property is sensitive to microstructure characterization, such as grain size, grain boundary characterization and amount of precipitations, which can be adjusted by hot extrusion process [7]. Furthermore, grain size control and microstructure uniformity also make great sense for the superior corrosion resistant property of alloy 690 [8] and hot deformation plays a critical role here [9,10]. Studies also show that the creep resistance of alloy 740 is related with grain size [11]. The grain size and microstructure can be controlled and adjusted during hot deformation. Hence, hot deformation is of great importance for property control and improvement of nickel-base superalloys.

Generally, the manufacture process of nickel-base superalloy pipes is complicated with a series of procedures, such as homogenization, hot extrusion, cold rolling and heat treatment [12]. Hot extrusion is the key technology in the whole manufacture process, during which many problems can take place. A typical schematic diagram of hot extrusion process is shown in Fig. 1 and the main components are marked in the figure. In the hot extrusion process, the pressing stem pushes the billet forward by the dummy block. The alloy flows out of the die, and the extruded part is called the shell.

The deformation resistance of alloy increases during hot extrusion and sudden stop of the extruder may occur when the deformation resistance exceeds the capacity of the machine. Cracks of shell, surface defects and uneven grain size are also the common failure cases during hot extrusion that seriously affect the quality of the products [13]. Moreover, the microstructure quality after hot extrusion directly determines whether the following procedures can be carried out smoothly and quality of finished pipe. As to the above reasons, there are two questions that need to be made clear: how to extrude the tube successfully and how to obtain the desired microstructure by hot extrusion.

In order to get excellent high temperature properties, nickel base

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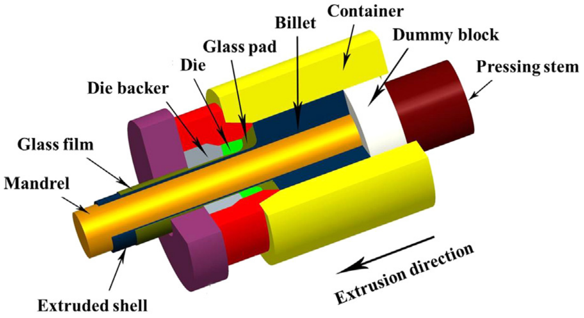

Fig. 1. Schematic diagram of hot extrusion process.

superalloys usually contain large amounts of alloying elements, which leads to the difficulties of microstructure control during hot deformation process [14]. Previous studies about nickel base superalloys mainly focus on mechanical properties [15], long term aging stability [16], corrosion resistant properties [2,17,18] and high temperature oxidation behaviors [19]. Works have also been done on dynamic recrystallization (DRX) behavior by isothermal hot deformation compression test to investigate the DRX mechanism [20–22]. However, little attention has been paid on the microstructure evolution during actual manufacture process, resulting in the microstructure control lack of theoretical supports. As a result, there is an urgent need to establish a microstructure control system for nickel-base superalloys during hot extrusion process.

The above analysis and discussion indicate that the property of nickel-base superalloy is the response of microstructure, and the microstructure is controlled by hot extrusion process. However, there is no systematic control principle reported for hot extrusion of nickel-base superalloy. Hence, the present study aims at the process and microstructure control during hot extrusion in order to establish the relationship between hot extrusion parameters and microstructure evolution. A series of technical control principles are proposed based on actual manufacture and experimental study of different kinds of nickel-base superalloys (such as 028, G3, 690, 740 H and 617B). The proposed control principle can provide systematically theoretical guidance for hot extrusion process, which is beneficial for microstructure control and property improvement of nickel-base superalloy.

2. Materials and experimental procedure

The investigation of hot extrusion behavior aimed at horizontal extruder with borosilicate glass lubricant. The major compositions of the borosilicate glass lubricant were SiO_2, Al_2O_3, CaO, MgO, Na_2O and B_2O_3. The analysis was based on the practical manufacture facts, large amounts of experimental data and finite element simulations. Isothermal hot compression simulation and microstructure observation methods were enrolled to get a detailed understanding of hot deformation behavior and microstructure evolution characteristics. Finite element simulation was carried out by DEFORM-2D software to simulate the hot extrusion process based on the actual manufacture condition. In the simulation, the billet was meshed into four node's quadrangle element. The flow behavior data and microstructure evolution model were obtained by isothermal hot compression simulation serves for the precise microstructure prediction during finite element simulation.

Several typical nickel-base superalloys were involved, such as 028 and G3 for oil and chemical industry, 690 for nuclear field, 740 H and 617B for ultra-supercritical power plant. The nominal compositions of experimental alloys are listed in Table 1.

The experiments and simulations were served for the summarization of evolution laws in hot extrusion. The control principle can be used as theoretical guidance to maintain manufacture safety and microstructure controllability for hot extrusion of nickel-base superalloy.

3. Results and discussion

3.1. Proposal of control principle

The hot extrusion process control for nickel-base superalloy is extremely difficult. There are a number of hot extrusion parameters that has to be taken into consideration in process design. The functions of different parameters on microstructure and working conditions are various, and sometimes they may go against each other, arising great difficulty for the design and optimization of hot extrusion parameters. Hence, it is necessary to propose a control principle to limit the parameters in a certain scope and get desired microstructure by hot extrusion.

It should be pointed out that, in the investigation of hot extrusion process there are two important points that need to be taken into consideration: one is the safety extrusion of the shell without apparent defects and the other is the microstructure control. In order to get the extruded pipe with desired microstructure successfully, a six-factor principle is proposed for process control during hot extrusion as shown in Fig. 2. The temperature, loading, mould and lubrication principle was proposed to ensure the safety hot extrusion. Furthermore, the microstructure principle and precise microstructure principle aim at the microstructure control in order to obtain the desired microstructure by hot extrusion process. The combination of the six principles can supply theoretical reference for hot extrusion process control and parameters design.

The variations of field quantities (such as temperature of billet, loading of machine, grain size of shell and so on) with working parameters (such as preheating temperature, lubrication condition, extrusion speed and so on) are complicated. Hence, it is necessary to get a common used investigation method in the work. For this purpose, the variation of a certain field quantity P with hot extrusion parameters x should be first expressed by function as $P = P(x)$. The influence of hot extrusion parameters on field quantity can be obtained by finite element simulation. The enrollment of finite element simulation can describe the evolution during hot extrusion quickly and intuitively, saving much trial and error efforts. Then the upper limitation P_{max} and lower limitation P_{min} can be obtained by investigation of the field quantity characteristics. Afterwards the limiting condition is overlapped on the variation relationship to determine the parameter scope as shown in Fig. 3. The shadowed part between x_{max} (corresponding to the upper limitation) and the x_{min} (corresponding to the lower limitation) is the optimized working parameter range determined by the control principle. The effect of other control principles on working parameters can all be determined in the similar way.

3.2. Explanation of control principles

The hot extrusion process and variation of different field quantities with hot extrusion parameters are complicated. The details and effects of different control principles can be explained as following.

3.2.1. Mould principle

The shape and size of the pipe is determined by mould. The strength of mould material is limited by temperature. Serious softening occurs when temperature is too high, resulting in the decrease of dimensional accuracy of the pipe. Furthermore, the temperature of the mould is not constant and changes with hot extrusion parameters during extrusion process. The aim of mould principle is to ascertain that the optimized hot extrusion parameters can maintain the mould temperature in a proper range. For example, H13 die steel is widely used as die material in extruder. The maximum allowable temperature of this material is 650 °C. Hence, the highest temperature of the mould should be lower than 650 °C during hot extrusion process for the mould principle.