Journal of Manufacturing Processes 34 (2018) 140–147

Contents lists available at ScienceDirect

Journal of Manufacturing Processes

journal homepage: www.elsevier.com/locate/manpro

# Research on precise control of microstructure and mechanical properties of Ni-based superalloy cylindrical parts during hot backward flow spinning

Gangfeng Xiao, Ningyuan Zhu, Jinchuan Long, Qinxiang Xia*, Weiping Chen

*Guangdong Provincial Key Laboratory of Precision Equipment and Manufacturing Technology, School of Mechanical and Automobile Engineering, South China University of Technology, Guangzhou 510640, China*

ARTICLE INFO

*Keywords:*
Haynes 230 alloy
Hot backward flow spinning
Hot processing map
Microstructure
Mechanical properties

ABSTRACT

Ni-based superalloy cylindrical parts widely used in the fields of aviation and aerospace have high requirements for the microstructure and mechanical properties. Hot flow spinning is an effective forming technology for manufacturing cylindrical parts with thin walls. The high-temperature plane strain compression test was put forward as the physical simulation test of hot backward flow spinning (HBFS) of cylindrical parts, and a new method for controlling the microstructure and mechanical properties of spun parts precisely based on hot processing map was proposed as the basis of selecting the reasonable processing parameters of HBSF. The results show that the relationships between the large true strains and stresses of Haynes 230 alloy during HBFS can be obtained effectively by the high-temperature plane strain compression test; the reasonable processing parameters which are beneficial for dynamic recrystallization and hot plastic deformation can be selected directly on the basis of the hot processing map. The influence of the processing parameters of HBSF on the microstructure of Haynes 230 cylindrical spun workpiece was also investigated, the results show that the influence of thinning ratio and forming temperature on the microstructure of the spun workpiece is remarkable, while the average grain size of spun workpiece decreases slightly with the increasing of feed rate. The yield strength and tensile strength of the Haynes 230 cylindrical spun part at the temperature of 800°C are both increased obviously compared with the original cylindrical blank, and the elongation is also slightly increased, which is particularly helpful in the high-temperature service of the Ni-based superalloys.

## 1. Introduction

Ni-based superalloys have been widely used for manufacturing the core hot-end parts of aerospace engine combustors and gas turbines due to the excellent high-temperature mechanical characteristics, outstanding oxidation and corrosion resistances, and good fatigue properties [1,2]. However, the Ni-based superalloys exhibit the high deformation resistance, poor plasticity, and large work hardening rates. For example, when the pre-deformation of the Haynes 230 alloy Ni-based superalloy (Haynes 230) reaches 30%, the elongation of the material decreases sharply from 46% to 14% [3]. Therefore, it is hard to be deformed at room temperature [4].

Hot flow spinning is an effective forming technology for manufacturing cylindrical parts with thin walls due to its enhanced formability, low deformation resistance, and high forming precision [5]. The mechanical characteristics of the material are largely depended on its microstructure [6]. The microstructure evolution during hot flow spinning is influenced by many factors, including the forming temperature, the feed rate of roller and the thinning ratio of wall thickness of cylindrical blank, and the hot forming mechanism is terrifically complex due to the effect of the thermal-mechanical coupling [4]. Therefore, the precise control method of the microstructure and mechanical properties during HBFS was investigated to obtain the cylindrical pats of Haynes 230 alloy with high dimensional accuracy and excellent mechanical properties.

As is well known, exploring the mechanism of microstructure evolution throughout the entire hot forming process is essential for the final products to achieve the desired excellent mechanical properties [7]. Hot processing map, as the combination of the maps of power dissipation and instability [8], is an effective method for optimizing the processing parameters and controlling the microstructure and mechanical properties during hot plastic forming [9]. The microstructure evolution mechanisms such as dynamic recovery, dynamic recrystallization (DRX), wedge cracking, cavity generation, localized flow and adiabatic shear band can be predicted by hot processing maps under different deformation conditions [10], and the 'stable region' and 'instability region' of hot plastic deformation can be obtained. Therefore, the aims of optimizing the processing parameters and avoiding the

* Corresponding author.
*E-mail address:* meqxxia@scut.edu.cn (Q. Xia).

https://doi.org/10.1016/j.jmapro.2018.05.034
Received 27 November 2017; Received in revised form 22 May 2018; Accepted 30 May 2018

microstructure defect can be achieved [11]. Zhang et al. [12] constructed the hot processing map of Ni-Cr-Mo-based C276 superalloy during hot compression process and observed the microstructure evolution at the strain of 1.0 under different temperature and strain rate. The results show that the fine and homogeneous recrystallization grain structure can be obtained with the high efficiency of power dissipation. He et al. [13] established the hot processing maps of a new P/M Ni-based superalloy during hot forging process and observed the deformed microstructure within the instability regions. The results indicate that the instability regions are normally located at strain rates higher than 0.1/s and are in the forms of adiabatic shear bands. Xu et al. [14] constructed the hot processing map of steel 42CrMo during hot ring rolling and optimized the deformation path of the deformed ring. The results show that the feeding strategy can be designed reasonably according to the hot processing map, and the desired and homogeneous microstructure without defect after hot ring rolling is obtained. At present, the investigations of hot processing maps mainly focus on the hot compression deformation, hot forging and hot rolling processes, few literatures were reported about the processing optimization or the precise control of the microstructure and mechanical properties based on hot processing maps during HBFS of cylindrical parts.

In this study, the relationships between the large true strains and stresses of Haynes 230 alloy during HBFS were obtained by means of the high-temperature plane strain compression (HTPSC) test. The hot processing map based on dynamic material model was constructed by combining the maps of the power dissipation and instability. The precise control of the microstructure and mechanical properties of Haynes 230 alloy cylindrical parts during HBFS was realized on the basis of the constructed hot processing map.

## 2. Physical simulation test for hot backward flow spinning of Haynes 230 alloy

Flow spinning, classified as a power spinning process, is an important method to manufacture hollow cylindrical parts with thin-walled thickness (Fig. 1) [5,15]. For manufacturing of cylindrical parts, backward spinning is commonly used. During backward spinning, the deformed material at the contact zones is in a state of three-dimensional compressive stress (Fig. 2), which is suitable for forming materials with poor ductility [16].

The thickness of the cylindrical blank decreases under the pressing of the rollers during flow spinning, and the deformed material flows toward the axial direction, where the flowing resistance is the smallest; the flowing along the tangential direction is difficult and small, which can be ignored [17]. Therefore, the strains at the deformation zone during backward flow spinning can be treated as the state of plane strain, i.e. the tensile strain along the axial direction $\varepsilon_a$, and the compressive strain along the radial direction $\varepsilon_r$ (Fig. 2) [18].

The uniaxial tensile test is usually adopted for the physical simulation test to investigate the deformation characteristics of material during flow spinning [19]. However, the maximum true strain obtained by the uniaxial tensile test is small, the maximum true strain of Haynes

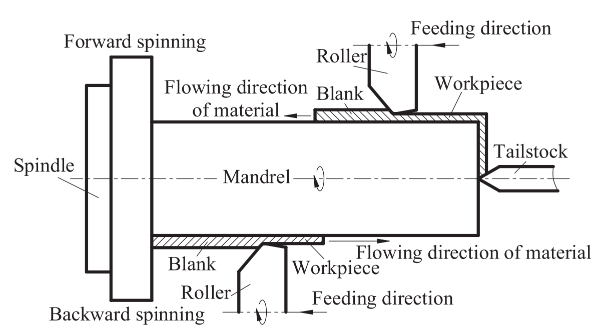


**Fig. 1.** Schematic illustration of the flow spinning of a cylindrical part.

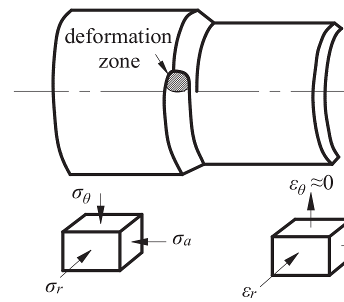


**Fig. 2.** Stress and strain during the flow spinning of a cylindrical part.

230 alloy obtained by the uniaxial tensile test is only 0.38 [20], while the equivalent strain obtained by the flow spinning is relatively large due to the minimum thinning ratio of wall thickness $\Psi_t$ should be larger than 30% [20]. According to the Eq. (1) [21], the equivalent strain $\bar{\varepsilon}$ is 0.41 when $\Psi_t$ is 30%, and the necessary $\Psi_t$ for the generation of the DRX during HBFS is normally larger than 30% based on the previous experiment of the authors. Therefore, the high-temperature plane strain compression (HTPSC) test was put forward to be the physical simulation test of the HBFS to obtain the relationships between the large true strains and stresses of the Haynes 230 alloy.

$$\bar{\varepsilon} = \frac{2}{\sqrt{3}}\ln\frac{1}{1-\psi_t} \quad (1)$$

where $\bar{\varepsilon}$ is equivalent strain; $\Psi_t$ is thinning ratio.

Haynes 230 alloy is a kind of solid-solution strengthened alloy containing the single austenite phase. Table 1 shows the chemical compositions of the alloy. The specimens used in this study were solution-treated at 1230 °C for 60 min before HTPSC test and HBFS. The HTPSC test was carried out on the Gleeble 3500 thermal simulation testing machine at temperatures ranged from 950 °C to 1200 °C with an interval of 50 °C, and strain rates of 0.01/s, 0.1/s, 1/s, and 10/s. The dimension of the tested specimens is 10 mm × 15 mm × 20 mm, and the specimen was compressed through two flat anvils under a certain strain rate, the lengthwise direction of the anvils is perpendicular to the surface of 10 mm × 15 mm of the specimen (as shown in Fig. 3). All specimens were heated at the test temperature with a heating rate of 10 °C/s and held for 5 min. and then compressed, the total true strain is larger than 1. The compressed specimens were immediately water-quenched to the room temperature after testing in order to preserve the microstructure formed at the high-temperature deformation. Fig.4 shows the photographs of the specimens obtained before and after the HTPSC test. It shows that thickness of the specimen beneath the anvil thins and spreading deformation occurs along the both sides of the anvil (X direction in Fig.4), no deformation is observed along the length direction (direction Y in Fig. 4). It indicates that the deformation area of the tested specimens is in the state of the ideal two-dimensional plane strain.

## 3. Construction of hot processing map based on dynamic material model

According to the dynamic material model (DMM), the process of hot plastic deformation of metal material is the process of power dissipation, and the total absorbed energy $P$ of the unit volume of the deformed material per unit time during hot deformation can be divided into the dissipation content $G$ and dissipation co-content $J$, and it can be

**Table 1**
Compositions of Haynes 230 Ni-based alloy (wt.%).

| Ni | Cr | W | Mo | Co | Fe | Mn | Si | Al | C | La | B |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Bal | 22.64 | 12.83 | 2 | 3.83 | 0.58 | 0.91 | 0.4 | 0.56 | 0.1 | 0.02 | 0.005 |