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Quantitative formability estimation of ring rolling process by using deformation processing map☆

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ABSTRACT

Studies on quantitative formability estimation by using deformation processing map have been performed to estimate deformation characteristics of SAF2205 duplex stainless steel during ring rolling process. To develop deformation processing map, dynamic materials model has been used on the basis of stress-strain relationships from Gleeble compression test. As a quantitative formability index, summation of η_{ij} (efficiency of power dissipation for i-th unit deformation group in j-th slicing plane) multiplied by area fraction of unit deformation group (A_{ij}) has been suggested. η_{ij}-value for unit deformation group was determined from deformation processing map of which temperature and strain rate can be obtained by finite element method. For the feasibility analysis, the optimum blank dimension at various operating temperatures has been determined on the basis of formability index. The analysis result strongly confirms that the proposed formability index can provide a reliable guide in process design of ring rolling process.

1. Introduction

The ring rolling process has widely been used in the production of seamless rings for plant facilities, gas turbine, aerospace and jet engine parts. A generalized ring rolling mill has three sets of rolls as shown in Fig. 1. First, a set of radial rolls including the mandrel and main roll which controls radial thickness of ring. Secondly, a set of axial rolls which reduces or restricts height of ring. Finally, guide rolls maintain the circular shape and accurate position of ring during ring rolling process. The advantages of ring rolling process are uniform quality, short production time, smooth surface finish and saving in material cost.

In general, ring rolling process is hard to design due to a lot of factors such as reduction ratio of radial thickness and height of ring, initial blank dimensions and rotational speed of main roll. If these factors are not optimized, final product has high probabilities having defects such as fishtail, tilting and ellipsoidal defect. Many studies to optimize ring rolling process have been carried out based on experimental and theoretical methods. Johnson et al. (1968) experimentally studied rolling force, rolling torque and pressure distribution, Boucly et al. (1988) proposed physical model to simulate the ring rolling process, Ryoo et al. (1986) used upper bound method to calculate rolling torque, Kim et al. (2012) analyzed defect characteristic by physical modeling.

In recent years, many researches try to apply finite element method to ring rolling process. Huisman and Huetink (1985) suggested combined Eulerian–Lagrangian finite element formulation, Kim et al. (1990) performed three dimensional finite element methods with two kinds of mesh system, Xu et al. (1991) solved finite element model of rigid plastic material, Allwood et al. (2005a,b) summarized overall development of ring rolling process, Allwood et al. (2005a,b) also described techniques for investigation of ring rolling process and Nam et al. (2012) predicted optimized blank through finite element method and physical modeling.

Furthermore, many studies to characterize hot formability and defects of ring rolling have been performed based on dynamic materials model, atomic model, ductile fracture model and Ziegler model. Murty et al. (2000) consider flow instability factor and suggest Ziegler instability model that can reliably analyze hot formability.

In this study, formability of ring rolling process has been quantitatively estimated by using deformation processing map based on dynamic materials model. Deformation processing map indicate the efficiency of power dissipation (η) at constant temperature

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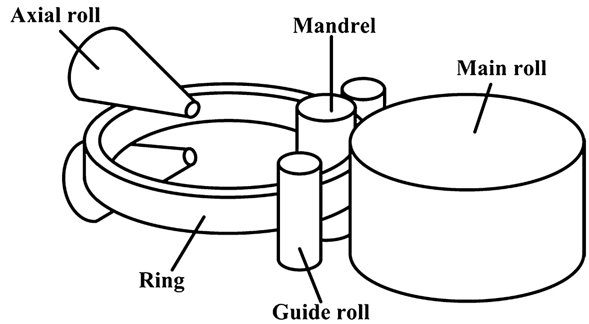

Fig. 1. Schematic of ring rolling mill.

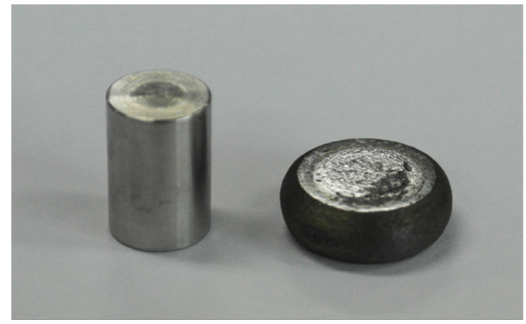

Fig. 2. Specimen before and after compression test.

and strain rate, but it does not provide representative quantitative evaluation. During ring rolling process, the deformation of ring is not uniform. Therefore, the volume of deforming ring need to be divided into unit deformation group that has similar temperature and strain rate. As a quantitative formability index (FI), summation of η_{ij} (efficiency of power dissipation for i-th unit deformation group in j-th slicing plane) multiplied by area fraction of i-th unit deformation group has been suggested. In metallurgical point of view, FI means the efficiency of power dissipation through the microstructural evolution. To find out variations of temperature and strain rate during deformation, finite element analysis had been performed at various blank geometries and deformation temperatures.

2. Experimental procedure

2.1. Materials

Chemical composition of SAF2205 duplex stainless steel used in this study is shown in Table 1. Duplex stainless steels are widely used in oil extraction, chemical and ocean industries due to an excellent combination of mechanical properties and corrosion resistance. These characteristics rely on dual-phase microstructure comprised by austenite and ferrite. But, drawbacks of duplex stainless is deformation defects such as edge cracks or shear band due to the difference in thermal deformation characteristics of constitutive phases(ferrite and austenite). Also, during heat treatment at temperature from 700 to 900 °C, mechanical and corrosion properties are deteriorated due to precipitation of harmful second phases such as sigma and chi phases.

Liu et al. (2013) studied effect of deformation mode on microstructure. Chen et al. (2011) characterized hot working properties of 2205 duplex stainless steel based on processing map.

2.2. Hot compression test

Hot compression test was conducted on a Gleeble3500 thermo-mechanical simulator at the temperature range of 900–1200 °C and strain rate range of 0.01–50 s^{-1}. The cylindrical specimens of 15 mm in height and 10 mm in diameter machined directly from the billet (Fig. 2). The specimens were preheated to 1250 °C and held for 250 s prior to deformation for temperature and composition homogenization. Then, specimen is cooled to deformation temperature at the cooling rate of 5 °C s^{-1}. Before compression test, each specimen was held for 20 s to eliminate thermal gradients. To reduce the friction between the specimen and the die, the mica plate was placed between them.

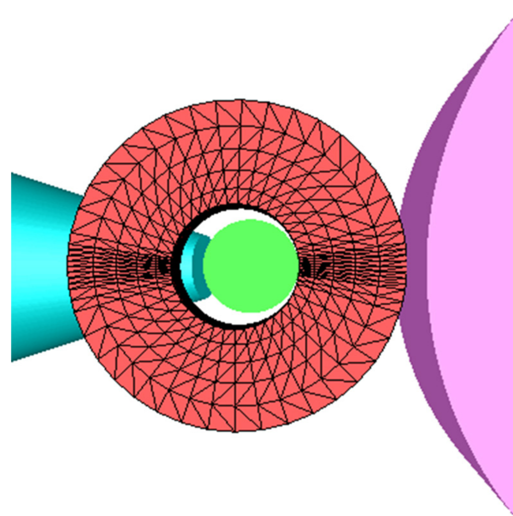

Fig. 3. Fine mesh is constructed in roll gap zone.

2.3. Finite element analysis

Finite element analysis was conducted by commercial simulation program FORGE-3D^{TM} which uses Hansel-Spittel rheology law containing thermo-mechanical conditions to define material flow.

Ring rolling simulations were carried out using an Arbitrary Lagrangian–Eulerian (ALE) approach and a coupled thermo-mechanical tetrahedron element. When using the ALE technique in engineering simulations, the computational mesh inside the domains can move arbitrarily to optimize the shape of elements, while the mesh on the boundaries and interfaces of the domains can move along with materials to precisely track the boundaries and interface of a multi-material system. ALE has lower computational time because fine mesh is constructed in deformation zone while coarse mesh is maintained in material zone (Fig. 3). The process condition used in FE analysis is summarized in Table 2.

To estimate the effects of initial blank dimension and temperature on formability of ring rolling process, finite element analysis at various blank geometries and temperature range of 900–1200 °C have been performed. The dimensions of target product were

Table 1
Composition of SAF2205 duplex stainless steel [wt%].

Fe	C	Cr	Ni	Mo	N	Mn	Cu
REM.	0.02–0.025	22.0–22.8	5.0–5.8	2.6–3.0	0.10–0.20	1.3–1.5	0.2–0.22