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Influence of ring growth rate on damage development in hot ring rolling

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ABSTRACT

As an incremental forming process of bulk metal, ring rolling provides a cost effective process route to manufacture seamless rings. In the production of hot rolled rings, defects such as porosity can sometimes be found in high alloyed steel, manufactured from ingots having macro-segregation. For the reduction of the waste of material and improvement of product quality, a better understanding of the relations between parameters in the hot ring rolling process and the occurrence of porosity is needed.

In this study round bars were used to manufacture rings on an industrial ring rolling mill. Different ring growth rates were applied to investigate the influence on the occurrence of porosity in the final rings. The hot rolled rings were inspected by ultrasonic testing, of which the results were also validated by metallographic investigation.

In addition to the experimental investigations, coupled thermo-mechanical multi-stage finite element (FE) analysis was performed with integrated adaptive motion control of the rolls. A damage indicator was implemented in a user-defined elasto-viscoplastic material model. The deformations, stresses as well as temperature history from preform forging were included as initial conditions for the rolling stage. Damage indication from the numerical model matches the experimental result in the considered process conditions.

In spite of the suggestion of a more careful process when a low ring growth rate is used in hot ring rolling, experimental and numerical studies demonstrate that with a low ring growth rate there is an increased susceptibility to damage as compared to application of a high ring growth rate.

1. Introduction

Forming a metal above its recrystallization temperature requires much less force and power than cold forming does because of its reduced yield strength and limited strain hardening. The formability and ductility of a metal increase at high temperature. Therefore through hot ring rolling a larger deformation and a wider range of ring cross sections can be achieved than by cold ring rolling. Tiedemann et al. (2007) determine the material flow distribution for radial profile ring rolling. Their investigations on wax-based model material show a high flexibility of the hot ring rolling process.

A typical hot ring rolling process includes preform forging and ring rolling as shown in Fig. 1. The billet is heated to a temperature above the recrystallization temperature of the material. The forming process begins with the upsetting of the hot billet. Next a punch forms a cavity and leaves only a thin web of metal at the hole bottom. In the piercing step, another punch pierces the billet to remove the web of metal. The billet with a complete hole in the center is referred to as preform and is then rolled on a ring rolling mill.

During radial–axial ring rolling, two rolling processes are done simultaneously, radial and axial rolling. In the radial stage, the ring thickness is gradually reduced by reduction of the gap between the main roll and the mandrel (see Fig. 1). The axial stage serves to control the final height of the ring by feeding the upper axial roll towards the lower axial roll. Both processes involve local deformation increments in perpendicular directions which are applied typically between 10 and 100 times to produce one ring. At the same time, the ring cools down at the surface and heats up due to dissipation of heat generated during plastic deformation and friction

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D_f	final ring outer diameter
σ_v	viscous stress
$\dot{p}$	equivalent plastic strain rate
σ_{eq}	equivalent stress
r	isotropic hardening variable
σ_f	flow stress
p	equivalent plastic strain
T	temperature
σ_0^*	strain and strain-rate independent stress
σ_w	work hardening stress
σ_0	initial yield stress at room temperature
σ_u^*	saturated value of exponential hardening
σ_{u0}	saturated value of exponential hardening at room temperature and at quasi-static threshold rate
C_T	temperature dependence coefficient
C_p	rate dependence coefficient
$\dot{p}_0$	quasi-static threshold rate
p_f	fracture strain
σ_h	hydrostatic stress
Ω	damage indicator
t	time point, current
υ_T	mean velocity of ring at inlet of radial roll gap
S	ring thickness at inlet of radial roll gap
υ_t	mean velocity of ring at outlet of radial roll gap
s	ring thickness at outlet of radial roll gap
υ_H	mean velocity of ring at inlet of axial roll gap
H	ring thickness at inlet of axial roll gap
υ_h	mean velocity of ring at outlet of axial roll gap
h	ring thickness at outlet of axial roll gap
υ_M	tangential velocity of main roll
D_m	mean diameter of ring
υ_A	tangential velocity of axial rolls
L_m	mean circumference of ring
L_i	half mean circumference between inlet of radial roll gap and outlet of axial roll gap
L_o	half mean circumference between outlet of radial roll gap and inlet of axial roll gap
D	outer diameter of ring
υ_r	feed rate of mandrel
t_0	time point, start of ring rolling
s_i	initial ring thickness
V_i	initial ring volume
δs	ring thickness reduction per pass
δh	ring height reduction per pass
υ_a	feed rate of upper axial roll
$\dot{D}$	ring growth rate
Δh_{total}	total ring height reduction
Δs_{total}	total ring thickness reduction
s_f	final ring thickness
h_i	initial ring height
α	opening angle of guide roll arms
D_g	guild roll diameter
R_0	initial ring radius
R	current ring radius
R_a	radius of rotation plane of axial rolls at mean radius of ring
R_m	mean radius of ring
S_x	coordinate of sensor node
υ_x	velocity of sensor node
n_A	rotation speed of axial rolls
n_M	rotation speed of main roll
υ_{Ar}	radial velocity of axial rolls
α_A	semi-vertical angle of conical axial rolls

between ring and rolls. As a consequence, the material experiences a very complex thermo-mechanical deformation history.

An important parameter in the ring rolling process is the ring growth rate, the rate of growth of the ring's outer diameter. The main roll usually rotates at a constant speed throughout the entire process. Therefore, the desired ring growth rate is controlled by the feed rates of the mandrel and the upper axial roll.

While the thickness of the ring is being reduced in the radial stage, simultaneously a slight increase of the height is observed. A similar effect is observed in the axial stage, where height reduction is accompanied with a slight increase in thickness. This phenomenon is referred to as the spread.

The ring rolling process has been subject of a number of experimental and numerical studies. Allwood et al. (2005) describe the development of the ring rolling technology in a thorough literature review. With increasing demand on product life time, optimization of process parameters to improve damage tolerance of the product in service becomes one of the key challenges in ring rolling.

The feed rate is a critical process parameter in the ring rolling process because the relative motions of radial and axial rolls must be controlled to achieve stable rolling, efficient reduction, and accurate final geometry. Many studies have been done to investigate the influence of the feed rate defined rolling schedule on the quality of the final ring. Using slip line theory, Hawkyard et al. (1973) find that in cold ring rolling a sufficiently high feed rate should be applied to avoid tensile stresses in the center of the ring's cross section. Tensile stresses predispose the material to internal cracking. Mamalis et al. (1976) examine the deformation mode of tellurium lead and aluminum alloy rings. They conclude that higher feed rates produce a more rectangular spread. Ryoo et al. (1986) find that as the feed rate increases, the torque of the main roll increases and the force on the mandrel decreases. The influence of feed rate on the mandrel force is less than that on the roll torque. Boucly et al. (1988) simulate the ring rolling with wax-based model materials. From the occurrence of fish tails (uneven spread) it is found that for a certain ring geometry and feed rate of the mandrel, the ratio of radial to axial rolling as well as the rolling curve have to be adjusted. Kluge et al. (1994) develop a new radial–axial rolling strategy to prevent overheating of the spread bulges and to make strain distribution more even. Radial and axial feeding are applied alternately in the proposed rolling schedule. Lin and Zhi (1997) analyze the maximum and minimum feed rates. The minimum feed rate is determined by plastic penetration and the maximum feed rate is determined by bite condition. Yan et al. (2007) propose a mathematical model to plan feed rate for a constant ring growth rate. They conclude that the ring grows uniformly and stably when the ring growth rate is constant. Sun et al. (2008) investigate strain and temperature distribution of the hot rolled ring using a FE model and conclude that a high feed rate improves the strain and temperature uniformity. Sun et al. (2010) analyze the effects of feed rate on micro structural evolution during hot ring rolling of AISI 5140 steel by a FE model. They show that increase of feed rate enlarges the regions of recrystallization. In addition, the distribution of recrystallization becomes more uniform. Zhou et al. (2011) study forming defects in hot rolling of aluminum alloy using FE simulation and find that a high ratio of axial to radial feed per revolution leads to less uniform deformation.

Under some process conditions defects such as porosity can be found in rings produced from high alloyed steels. High alloyed steel ingots tend to contain macro segregations (Campbell, 2003). In none of the aforementioned studies on the effect of feed rate, its influence on damage development in the bulk of the ring has been subject of investigation.

In this work the influence of ring growth rate on the occurrence of macro defects in the bulk of the ring is studied. Billets were hot forged and then ring rolled with different feed rate programs,