Influence of feed rate on damage development in hot ring rolling

Chao Wang\(^a,\)*, Ton van den Boogaard\(^b\), Edin Omerspahic\(^c\), Viktor Recina\(^c\), Bert Geijselaers\(^b\)

\(^a\)Materials innovation institute (M2i), P.O. Box 5008, 2600 GA, Delft, Netherlands
\(^b\)Faculty of Engineering Technology, University of Twente, P.O. Box 217, 7500 AE Enschede, Netherlands
\(^c\)SKF Group, Manufacturing Development Center, SE-415 50, Gothenburg, Sweden

Abstract

As an incremental forming process of bulk metal, ring rolling provides a cost effective process route to manufacture seamless rings. Applications of ring rolling cover a wide range of products in aerospace, automotive and civil engineering industries. Under some process conditions, defects such as porosity can sometimes be found in hot rolled rings, which are manufactured from high alloyed steel ingots having macro segregations. For the reduction of the waste of material and improvement of product quality, a better understanding of the relations between segregation levels in the ingot, process parameters in the hot ring rolling and the occurrence of porosity is needed. In this research, a coupled thermo-mechanical multi-stage finite element model is used to simulate the hot ring rolling process including preform forging. The deformations, stresses and strains from the preforming steps are included as initial conditions for the rolling stage. Subroutines are implemented to represent the control algorithm for the motion of the rolls. A damage indicator is implemented in the material model. Simulations with different feed rate curves are carried out in order to see the influence on the occurrence of porosity. Hot ring rolling experiments in an industrial rolling mill are conducted to validate the numerical study. The results of simulation and experiment show good agreement.

© 2014 The Authors. Published by Elsevier Ltd.

Selection and peer-review under responsibility of Nagoya University and Toyohashi University of Technology.

Keywords: Hot ring rolling; Finite element model; Damage indicator; Feed rate

* Corresponding author. Tel.: +31 53 4894069; fax: +31 53 4893471.
E-mail address: c.wang@m2i.nl
1. Introduction

The production of seamless rings with different dimensions is performed by the ring rolling process. A typical hot ring rolling process includes preform forging and ring rolling as shown in Fig. 1. During radial-axial ring rolling, two rolling processes are done simultaneously, radial rolling and axial rolling. In the radial stage, the ring thickness is gradually reduced, while the axial stage serves to control the final width of the ring. At the same time, the ring cools down at the surface and heats up due to dissipation of heat generated during plastic deformation work. As a consequence, the material experiences a very complex thermo-mechanical deformation history.

Fig. 1. Process chain of hot ring rolling: (a) preform forging and (b) ring rolling [7].

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 of long product life cycle, optimization of process parameters to improve damage tolerance or creep resistance of the product in service becomes one of the key challenges in ring rolling. Among others, the feed rate of the mandrel is already being considered as a critical process parameter in experimental and numerical analyses of the ring rolling process because the relative motion of radial and axial rolls must be controlled to achieve a stable expansion of the ring diameter. Many studies have been done to investigate the influence of the feed rate-defined rolling schedule on the quality of the ring product. Using slip line theory, Hawkyard et al. (1973) suggest a sufficiently high feed rate in cold ring rolling to avoid tensile stresses in the central section of the ring, which predispose the material to internal cracking. Mamalis et al. (1976) examine the deformation mode of tellurium lead and aluminum alloy rings rolled on an experimental radial ring rolling mill and conclude that the higher feed rates produce more rectangular spread distribution. Kluge et al. (1994) develop a new radial-axial rolling strategy to prevent the overheating of the spread bulges and to make the strain distribution more even. The radial and axial feeding are applied alternately in the proposed rolling schedule. Lin and Zhi (1997) analyze the maximum and minimum feed rates based on the plastic penetration and bite condition. Yan et al. (2007) propose a mathematical model to plan feed rate for a constant ring outer diameter growth. Sun et al. (2008) investigate the strain and temperature distribution of the hot rolled ring using a FE model and conclude that a high feed rate increases the strain and temperature uniformity. Zhou et al. (2011) study the forming defects in hot rolling of aluminum alloy using FE simulation and find that a low ratio of radial to axial feed per revolution leads to more non-uniform deformation. Despite the aforementioned studies on feed rate, its influence on internal damage in the bulk of the ring needs further investigation.

This work investigates the influence of feed rate on the damage development of hot ring rolling. The selected samples are hot forged and ring rolled under different feed rate programs. The influence of feed rate is indicated numerically from FE analyses by a damage indicator and identified experimentally from hot ring rolling trials with the help of ultrasonic testing (UT).
2. Test design

2.1. Sample selection

The material used in this research is 100CrMnMoSi8-4-6 steel. One of the inevitable sources of damage in metal forming processes is the existence of voids in the material of the billet. Casting ingots usually have micro size and macro size void type defects caused by shrinkage and gas evolution during solidification. For the purpose of this research, steel billets prepared for the tests are first cut near the segregation area of the ingot. Next, round bars of 80 mm in diameter and 205 mm in height are machined out of the centerline of the billets. All the bars are then inspected by UT so as to identify the initial quality of the samples. A great difference in terms of damage indication is observed in UT imaging. Finally, the samples are selected in such a way to represent relatively good material, which has no visible macro voids.

2.2. Test conditions

The selected samples are used to manufacture rings in field tests. The tests include all operations as in a typical hot ring rolling production system involving post heat treatment and machining. The initial hot working temperature is set at $T_0 = 1150 \, ^\circ C$. The temperatures are recorded by an infrared camera in order to see the temperature history of the process and its distribution on the work piece. In the ring rolling operation, three different conditions are prescribed with respect to the feed rate of the mandrel. For each feeding condition, the feed rate decreases gradually with ring thickness reduction to maintain a constant ring growth rate. The feed rates against wall thickness of the ring in time are plotted in Fig. 2, which represent high, intermediate and very low feed rate programs respectively.

![Fig. 2. Diagrams of feed rate of mandrel against wall thickness of the ring.](image)

2.3. Ultrasonic testing of rolled rings

To avoid possible cracking, rolled rings are put into a furnace for heat treatment. Moreover, the cold rings are grinded carefully to increase the precision of the UT. The automatic immersion testing method is used with 45° refracted shear wave in steel. The circumferential resolution and axial resolution are 0.3 mm and 0.2 mm respectively.

3. Finite element analysis

A coupled thermo-mechanical multi-stage finite element model has been built in the commercial FE code LS-DYNA to simulate the preform forging and ring rolling. A damage indicator is implemented in an elasto-viscoplastic material model with temperature dependency.
3.1. Material model

To model the plastic flow behavior of the material under hot ring rolling, a phenomenological model is used to describe flow stress and hardening. The flow stress $\sigma_f$ is defined as a function of equivalent plastic strain $\bar{\varepsilon}^p$, equivalent plastic strain rate $\dot{\bar{\varepsilon}}^p$ and temperature $T$. The model starts with a decomposition of the flow stress into a strain and strain-rate independent stress $\sigma_0$, a work hardening term $\sigma_w$ and a viscous stress $\sigma_v$.

$$\sigma_f = \sigma_0(T) + \sigma_w(\bar{\varepsilon}^p, \dot{\bar{\varepsilon}}^p, T) + \sigma_v(\dot{\bar{\varepsilon}}^p).$$ (1)

The model has 14 parameters that are obtained by fitting experimental results of 12 hot compression tests at 4 strain rates and 3 different temperatures using an optimization program in MATLAB. In Fig. 3 some of the true stress-strain curves are plotted for the experiments and the model.

Fig. 3. Calibrated numerical true stress-strain curves compared to experimental ones: (a) $T = 1000 \degreeC$ and (b) $\dot{\varepsilon} = 5 \text{s}^{-1}$. The stresses are normalized.

Materials are sensitive to hydrostatic tension if there exist micro voids. Based on stress triaxiality and equivalent plastic strain a damage indicator $D$ is proposed in this work as

$$D = \int_0^{\bar{\varepsilon}^p} \left( \frac{\sigma_h}{\sigma_{eq}} \right) d\bar{\varepsilon}^p \quad \text{with} \quad \langle \sigma_h \rangle = \frac{1}{2} (\sigma_h + |\sigma_h|),$$ (2)

where $\sigma_h$ is the hydrostatic stress, $\sigma_{eq}$ is the equivalent stress and $d\bar{\varepsilon}^p$ is the incremental equivalent plastic strain. Only the hydrostatic tension contributes to the damage indicator. The computed damage value is intended to indicate the damage level between different process conditions. A critical damage value has not been defined yet.

3.2. FE simulations of preform forging and ring rolling

The preform forging and ring rolling processes have been simulated by an efficient 2D to 3D procedure. The details are presented in Wang et al. (2013). The ring rolling simulation is carried out with integration of a control algorithm using simulation response data. Moreover, in this work the feed rate of the mandrel is controlled by the actual wall thickness of the ring to follow the desired ring growth rate. The cooling during the transport from the pre-forming station to the ring rolling mill is also considered by the thermal solver.

4. Results and discussion

FE modeling of plastic forming processes provides increased process understanding as the distribution of stress, strain and temperature can be examined. In Fig. 4 the temperature distribution and damage accumulation after the
pre-forming simulations are plotted as well as the equivalent plastic strain distribution of the hot rolled ring. Extremely high strain peaks are observed in the cross section corners of the rolled ring due to the constant formation and deformation of the spread bulges in radial-axial ring rolling. This may cause damage and defects in the region adjacent to them. However, due to the general low precision of hot forming and potential surface defects mentioned above, a portion of material is normally milled away. The more severe problem is the damage in the bulk of the ring which is hard to recover after forming.

Fig. 4. Contour plots of preform and rolled ring. (a) temperature distribution after pre-forming (°C), (b) damage indicator distribution of preform and (c) equivalent plastic strain distribution of rolled ring.

Fig. 5. Damage indication maps (left side) and UT images (right side) of rings rolled with different feed rate programs: (a) and (b) high feed rate A, (c) and (d) intermediate feed rate B, (e) and (f) low feed rate C. The color scale is numbered using logarithmic scale.
The results of ultrasonic testing are presented by the images at the right side of Fig. 5. The short edge of the image is the prolonged thickness of a ring, which is the quotient of real wall thickness divided by the refraction angle in the ultrasonic testing. The long edge represents the circumferential direction. The dark pixels represent the integration of damage indications, which might be voids. For the simulation results, the nodal values of damage indicator and the nodal coordinates are extracted to generate the damage indication map. The intention of this post-processing is to reproduce a damage inspection procedure similar to ultrasonic testing, for a direct and clear comparison. In the images at left side of Fig. 5, the x-axis is the center angle of a ring and the y-axis is the normalized wall thickness. The domain of a ring is then divided in a polar coordinate system into a number of boxes and each of them represents a bulk volume of a ring. The gray scale color indicates the mean damage value of one box. The values of 0.3 to 0.8 (0 to 1 equals the whole wall thickness.) in the y-axis mean that regions at inner and outer surfaces are excluded to avoid the effects of the strain peaks. Clearly, from both the simulation prediction and the experimental validation, the lowest feed rate (C), develops considerable macro voids that are concentrated in the center of the wall thickness. In contrast to the low feed rate condition, only very low amounts of macro voids are observed in the conditions with an intermediate feed rate B and a high feed rate A. From the formulation of the damage indicator, one reason is that the low feed rate leads to a triaxial tensile stress state in the center of the ring. Therefore, macro voids are formed by the coalescence of neighboring large micro voids.

5. Conclusion

The selected samples taken from volumes near the segregation area of an ingot and machined out to the billets are forged and hot ring rolled with different feed rate programs. The billets and the rolled rings have been inspected by ultrasonic testing to identify the damage levels. The whole process is simulated by a coupled thermo-mechanical FE model with integration of a user-defined material model with a damage indicator. The result of the damage indication in the simulation matches the experimental result well in the presented process conditions. Together, they reveal the hidden danger of using inappropriate low feed rate in the process of hot ring rolling.

Acknowledgements

This research was carried out under the project number M41.1.11418 in the framework of the Research Program of the Materials innovation institute M2i (www.m2i.nl). The industrial partner, SKF Group Manufacturing Development Centre is gratefully acknowledged for the contributions to this research.

References

Allwood, J.M., Tekkaya, A.E., Stanistreet, T.F., 2005. The development of ring rolling technology, Steel Research, 76/2/3: 11 1-120 and 76/7: 491-507.
Hawkyard, J.B., Johnson, W., Kirkland, J., Appleton, E., 1973. Analyses for roll force and torque in ring rolling, with some supporting experiments. International Journal of Mechanical Sciences 15, 873-893.
Kluge, A., Lee, Y.H., Wiegels, H., Kopp, R., 1994. Control of strain and temperature distribution in the ring rolling process. Journal of Materials Processing Technology 45, 137-141.
Lin, H., Zhi, Z.Z., 1997. The extremum parameters in ring rolling. Journal of Materials Processing Technology 69, 273-276.
Mamalis, A.G., Hawkyard, J.B., Johnson, W., 1976. Spread and flow patterns in ring rolling. International Journal of Mechanical Sciences 18, 11-16.
Sun, Z.-c., Yang, H., Ou, X.-z., 2008. Thermo-mechanical coupled analysis of hot ring rolling process. Transactions of Nonferrous Metals Society of China 18, 1216-1222.
Wang, C., Geijserls, H.J.M., Van den Boogaard, A.H., 2013. Multi-stage FE simulation of hot ring rolling. In: The 11th International Conference on Numerical Methods in Industrial Forming Processes: NUMIFORM 2013, Shenyang, China, AIP Conference Proceedings, 1532, 1014-1019.
Yan, F.-L., Hua, L., Wu, Y.-Q., 2007. Planning feed speed in cold ring rolling. International Journal of Machine Tools and Manufacture 47, 1695-1701.
Zhou, J., Wang, F.-l., Wang, M.-h., Xu, W.-j., 2011. Study on forming defects in the rolling process of large aluminum alloy ring via adaptive controlled simulation. Int J Adv Manuf Technol 55, 95-106.